UNIVERSIDADE DE LISBOA
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STRENGTH TRAINING AND MUSCLE ARCHITECTURE

With special reference to effects of range of motion on muscle structure

Dissertação elaborada com vista à obtenção do Grau de Mestre em Treino de Alto Rendimento

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Abstract

The purpose of the present study was to investigate adaptations on vastus lateralis (VL) muscle size, pennation angle and force (torque max) to a 15 week training program with either a full or partial range of motion (ROM). Nineteen previously untrained students were randomly distributed in one of two groups: control (CG) (n = 8; age, 26.6 ± 5.2 years; height, 177 ± 5.3 cm; body mass, 75.7 ± 10.6 kg; means ± SD) or training (TG) (n = 11; age, 21.6 ± 3.5 years; height, 174 ± 4.5 cm, body mass, 71.0 ± 6.9 kg; means ± SD) group. In the TG, one of the subject's legs was randomly chosen to be trained with a full ROM (FULL) and the other partial ROM (PAR). Training consisted on 15 weeks of isokinetic training, with either a full (100º of knee flexion to 0º) or partial (60º of knee flexion to 0º) ROM. Pennation angle (PA) was measured with ultrasonography at 50% of total muscle length. VL maximum anatomical cross sectional area ($ACSA_{max}$), volume and regional ACSA (measured at 25, 50 and 75% of total muscle length - $ACSA_{25,\ 50,\ 75}$) was obtained with magnetic resonance imaging (MRI). Maximum torque was obtained isometrically with isokinetic dynamometer at 75º of knee flexion.

Together with PA, all muscle size measures increase significantly ($p<0.05$) from pre- to post-training. The changes were respectively for FULL and PAR, PA: 9.6 and 12.3%; $ACSA_{max}$: 5.3 and 4.1%; Volume: 5.1 and 4.6%. When comparing regional adaptations on muscle size of VL, the changes were respectively for FULL and PAR, $ACSA_{25}$: 3.0 and 2.9%; $ACSA_{50}$: 5.5 and 4.5%; $ACSA_{75}$: 6.9 and 6.7%. Although we verified a trend to a greater increase from proximal to distal site, we only found differences when comparing $ACSA_{50}$ and $ACSA_{75}$ to $ACSA_{25}$. In PAR and FULL maximal torque increased 27.9 and 33.3%, respectively. No significant differences ($p<0.05$) were found for PA, isometric knee extensor torque or any muscle size measures between training groups. As expected no significant changes ($p<0.05$) were found for the control group for any measured variable.

The present findings suggest that vastus lateralis adapts to training independent of ROM when muscle time under tension is similar.

Keywords: Muscle structure, muscle size, regional hypertrophy, muscle architecture, vastus lateralis, range of motion, strength training.

Resumo

O propósito do presente estudo foi investigar as adaptações no volume do músculo vastus lateralis (VL), ângulo de penação e força (momento máximo de força) a um programa de treino de força de 15 semanas com amplitude (ROM) total ou parcial. Dezanove estudantes previamente não treinados foram distribuídos aleatoriamente num de dois grupos: controlo (CG) (n=8; idade, 26.6 ± 5.2 anos; altura, 177 ± 5.3 cm; massa corporal, 75.7 ± 10.6 kg; média ± DP) e treino (TG) (n = 11; idade, 21.6 ± 3.5 anos; altura, 174 ± 4.5 cm, massa corporal, 71.0 ± 6.9 kg; médias ± DP). No TG, uma das pernas de cada sujeito foi aleatoriamente escolhida para ser treinada com uma amplitude total (FULL) e a outra parcial (PAR). O treino consistiu em 15 semanas de treino isocinético com uma amplitude total (100 a 0º de flexão do joelho) ou parcial (60 a 0º). O ângulo de penação (PA) foi medido através de ultrasonografia a 50% do comprimento total do músculo. A área de secção anatómica máxima ($ACSA_{max}$), o volume e a ACSA regional (medida a 25, 50 e 75% do comprimento total do músculo - $ACSA_{25,\ 50,\ 75}$) do VL foram obtidas através de ressonâncias magnéticas (MRI). O momento máximo de força foi obtido isometricamente com 75º de flexão do joelho.

Para além do PA, todas as medidas do tamanho do músculo aumentaram significativamente ($p<0.05$) do período pré para pós-treino. As alterações foram respectivamente para o grupo FULL e PAR, PA: 9.6 e 12.3%; $ACSA_{max}$: 5.3 e 4.1%; VL Volume: 5.1 e 4.6%. Quando comparadas as adaptações regionais do VL, as alterações foram respectivamente para o grupo FULL e PAR, $ACSA_{25}$: 3.0 e 2.9%; $ACSA_{50}$: 5.5 e 4.5%; $ACSA_{75}$: 6.9 e 6.7%. Apesar de se verificar uma tendência para maiores aumentos da região proximal para a distal, só foram verificadas diferenças quando comparadas as regiões $ACSA_{50}$ e $ACSA_{75}$ com a região $ACSA_{25}$. Para o grupo PAR e FULL o momento máximo de força aumentou significativamente 27.9 e 33.2%, respectivamente. Não foram verificadas diferenças significativas ($p<0.05$) entre PAR e FULL no PA, momento isométrico máximo de extensão do joelho e nas medidas de dimensão do músculo. Não foram verificadas alterações significativas ($p<0.05$) no grupo de controlo em todas as variáveis avaliadas.

Os resultados do presente estudo demonstram que quando o tempo sobre tensão é semelhante, o VL se adapta ao treino independentemente do ROM.

Palavras chave: Volume muscular, hipertrofia regional, arquitectura muscular, vastus lateralis, amplitude de movimento, treino de força

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List of abbreviations

ACSA	Anatomical cross-sectional area
$ACSA_{max}$	Maximal anatomical cross-sectional area
CSA	Cross sectional area
CV	Coefficient of variation
FL	Fascicle length
GL	Gastrocnemius lateralis
GM	Gastrocnemius medialis
HIIT	High intensity interval training
HIPT	High intensity power training
IGF	Insulin like growth factor
ICC	Intra-class correlation
MT	Muscle thickness
MU	Motor unit
MRI	Magnetic resonance imaging
Nm	Newton x meter
PA	Pennation angle
PCSA	Physiological cross-sectional area
QF	Quadriceps femoris
RF	Rectus femoris
RM	Repetition maximum
ROM	Range of motion
SD	Standard deviation
SEM	Standard error mean
TE	Typical error
TUT	Time under tension
US	Ultrasound
VL	Vastus lateralis
VM	Vastus medialis

1. Introduction

1.1. Statement of the problem

There are several factors contributing to force production (Cormie, McGuigan, & Newton, 2011; Folland & Williams, 2007). Given this, adaptations to resistance training have been investigated at a hormonal, metabolic, neural and morphological level.

From a hormonal point of view it is well known that an increased anabolic hormonal level strongly influence muscle hypertrophy through the stimulation of protein synthesis (Kraemer & Fleck, 1993; Kraemer et al., 1990; McCaulley et al., 2009). Likely, resistance training increases protein synthesis in a greater magnitude than protein breakdown, resulting on an increased muscle net protein balance (Kumar, Atherton, Smith, & Rennie, 2009; Phillips, Tipton, Aarsland, Wolf, & Wolfe, 1997; Yarasheski, Zachwieja, & Bier, 1993). Also, an increase in both anabolic and catabolic hormonal levels is expected as response to resistance training (Kraemer et al., 1999; Kraemer & Fleck, 1993; Kraemer et al., 1990; McCall, Byrnes, Fleck, Dickinson, & Kraemer, 1999; McCaulley et al., 2009; Wideman, Weltman, Hartman, Veldhuis, & Weltman, 2002), whereas the balance between these ultimately dictate the increase or decrease on net protein balance (Kumar et al., 2009; Phillips et al., 1997; Yarasheski et al., 1993). At a cellular level, this phenomenon can occur due to a number of complex signaling pathways which in turn are stimulated by the mechanical stress induced thru resistance training (Schoenfeld, 2010; Tidball, 2005; Toigo & Boutellier, 2006). Although there are other anabolic hormones (e.g. leptin, peptide F, estrogens), the most widely investigated are probably testosterone, growth hormone, insulin and insulin-like growth factors (IGFs) (Crewther, Keogh, Cronin, & Cook, 2006; Kraemer & Ratamess, 2005). The catabolic hormone that has received most attention is cortisol (Kraemer et al., 1999; Kraemer & Fleck, 1993; McCall et al., 1999; McCaulley et al., 2009). These hormones seem to be sensitive to many factors as sex, age, nutrition, training status and training methodology (Crewther et al., 2006; Kraemer & Ratamess, 2005). In particular, strength training characterized by high volume, high intensity and low intra-set rest intervals seems to lead to a greater acute increases in the hormonal level (Kraemer et al., 1999; Kraemer & Fleck, 1993; Kraemer et al., 1990; McCall et al., 1999; McCaulley et al., 2009; Wideman et al., 2002). Moreover, while an acute increased in anabolic hormones can be observed after strength training, chronically there seem to be no major changes on hormonal concentration arising from training (McCall et al., 1999; Wideman et al., 2002). An extensive review of the impact of manipulating these training variables can be found on the papers of Crewther et al. (2006) and Kraemer & Ratamess (2005).

Neural adaptations are expected as adaptation to resistance training (Gabriel, Kamen, & Frost, 2006). The disproportional greater increase in strength in comparison to muscle size observed during early exposure to resistance training protocol is one possible example of the adaptive potential of neural mechanisms (Moritani & DeVries, 1979). This can be explained by the observed increase in motor unit activation on untrained subjects (Häkkinen et al., 1998; Häkkinen, Alen, Kallinen, Newton, & Kraemer, 2000; Rabita, Pérot, & Lensel-Corbeil, 2000), although literature is inconsistent since no differences on motor unit activation after resistance training have been reported by some (Holtermann, Roeleveld, Vereijken, & Ettema, 2005). The level of motor unit (MU) activation expresses the number of recruited MU and their discharge rate (Gabriel et al., 2006; Sale, 2003). Therefore an increase in both recruitment (Patten, Kamen, & Rowland, 2001) and firing rate (Cutsem, Duchateau, & Hainaut, 1998; Patten et al., 2001) is expected as adaptation to strength training. Not only MU recruitment and firing rate seem to influence force production. Early activation of MU, training induced doublets, synchronization of MU are other examples of adaptations resulting from resistance training (Cutsem et al., 1998). The need for observation of a single motor unit to better understand neural adaptations arising from resistance training leads to methodological difficulties that makes scarce literature in comparison to other subjects. Thus, there are still a lot of controversies on the neural mechanisms that facilitate force production (Enoka & Fuglevand, 2001). An extended understanding of neural adaptations to resistance training can be found in the reviews of Sale (2003), Duchateau, Semmler, & Enoka (2006) and Gabriel et al. (2006).

Manipulation of program design variables (e.g. number of repetitions) strongly determines adaptations to resistance training (Anderson & Kearney, 1982; Campos et al., 2002; Stone & Coulter, 1994). Therefore, muscular adaptations in muscle size, strength and/or endurance can be partly explained by differences in the training intensity zone (i.e. different maximum repetitions zones, known as *repetition continuum*) (Campos et al., 2002). While heavy to moderate training (i.e. 3-5RM to 9-11RM) leads to increases in all muscle fiber type area and therefore greater increases in maximum strength, low load training (i.e. 20-28RM) appears to be best suited for increases in aerobic power, time to exhaustion and increase in muscular resistance (Campos et al., 2002). Another type of high volume resistance training is circuit training. This type of training consists on a set of exercises performed with little rest in between. Because the work rest ratio is greater in circuit training in comparison to traditional resistance training, circuit training seems to have beneficial effects on cardiovascular adaptations (Henry, Anshel, & Michael, 2006; Kaikkonen, Yrjämä, Siljander, Byman, & Laukkanen, 2000; Mosher & Underwood, 1994). More recently was implemented the term high intensity power training (HIPT). This type of training can be considered as high intensity interval training (HIIT) with recourse to resistance and bodyweight exercises. Being that, HIPT is very similar to circuit training but uses multi joint movements with high intensity (i.e. load, jumps, etc.) in combination with low rest between exercises (Smith, Sommer, Starkoff, & Devor, 2013). A very well known example of this type of training is *Crossfit*®. Recurring to this methodology, Smith et al. (2013) verified significant increases in VO_2max after 10 weeks of training. As reported by the authors, these increases were similar to previously research on HIIT and therefore a valid alternative when increases in maximal aerobic power are desired.

An increase in muscle size is expected as adaptation to resistance training. While historically studies of skeletal muscle required the dissecation of cadavers (Friederich & Brand, 1990; Lieber, Fazeli, & Botte, 1990; Wickiewicz, Roy, Powell, & Edgerton, 1983), progresses in imaging techniques and collecting of needle muscle biopsies allows for a better and more practical understanding of skeletal muscle function and structure. Given this, an increase in single muscle fibers cross sectional area (CSA) is expected after strength training (Aagaard et al., 2001; Akima et al., 1999; Andersen & Aagaard, 2000; Hikida et al., 2000; Sharman et al., 2001; Staron et al., 1994; Volek et al., 1999), whereas type II muscle fibers generally demonstrate greater increases in comparison to type I. More specifically a shifting of type IIX/B to type IIA is commonly observed after resistance training (Andersen & Aagaard, 2000; Hikida et al., 2000; Sharman et al., 2001). While needle biopsies are required to obtain a sample of the tissue for further analysis of single muscle fibers (i.e. microscopic level), less invasive methods can be used to obtain information of muscle size at a macroscopic level. Magnetic resonance imaging (MRI) or ultrasonography (US) are examples of equipment used by researchers to analyze muscle at a macroscopic level. From a macroscopic point of view, an increase in muscle size measured as muscle thickness (MT) (Kawakami, Abe, Kuno, & Fukunaga, 1995; Matta, Simão, & Salles, 2011; Starkey et al., 1996), physiological cross sectional area (PCSA) (Aagaard et al., 2001; Kawakami et al., 1995), anatomical cross sectional area (ACSA) (Aagaard et al., 2001; Kawakami et al., 1995; Rutherford & Jones, 1992) or muscle volume (Aagaard et al., 2001; Kawakami et al., 1995) can be observed as a result of resistance training. As non-linear changes in muscle size between muscles from the same muscle group (e.g. quadriceps) and even within the same muscle (e.g. vastus lateralis) have been reported, assessments of the muscle along its entire length are recommended (Blazevich, Gill, Bronks, & Newton, 2003; Häkkinen et al., 2001; Housh, Housh, Johnson, & Chu, 1992; McMahon, Morse, Burden, Winwood, & Onambélé-Pearson, 2013; Reeves, Narici, & Maganaris, 2004). Although muscle size is expected to increase as adaptation to resistance training, different magnitudes are reported in literature. Adaptations on muscle size are sensible to some training variables as training volume, type of contraction (Blazevich, Cannavan, Coleman, & Horne, 2007; Seynnes, de Boer, & Narici, 2007; Tesch, Ekberg, Lindquist, & Trieschmann, 2004), velocity/time under tension (Cormie, McGuigan, & Newton, 2010) or range of motion (Bloomquist et al., 2013; McMahon et al., 2013).

Muscle size and muscle force production are strongly influenced by fascicles arrangement (muscle architecture) within the muscle (Alegre, Jiménez, Gonzalo-Orden, Martín-Acero, & Aguado, 2006). Although previously cadaveric studies analyzed organization of fascicle geometry (Friederich & Brand, 1990; Lieber, Fazeli, & Botte, 1990; Wickiewicz, Roy, Powell, & Edgerton, 1983), progresses in imaging technology allows researchers to analyze it *in vivo*. Normally ultrasonography is the technique of choice for this type of assessments. Basically, a sonogram (ultrasonography image) is obtained from the echo of an emitted ultra-sound reflex on the different tissues and fascicle pennation angle (PA) and fascicle length (FL) are measured. Pennation angle (PA) is the angle measured between the fascicle and deep aponeurosis and fascicle length corresponds to the length of the fascile measured from the deep to superficial aponeurosis (Abe, Brown, & Brechue, 1999; Kawakami, Abe, & Fukunaga, 1993; Kumagai et al., 2000; Nimphius, McGuigan, & Newton, 2012). These parameters of fascicle geometry have some functional implications for muscle force production. Increases in strength arising from a traditional training intervention can be in part explained by the increase in PCSA (Aagaard et al., 2001; Fukunaga, Roy, Shellock, Hodgson, & Edgerton, 1996; Fukunaga et al., 2001). Because PCSA represents the amount of contractile material arranged in parallel (Wickiewicz et al., 1983), changes in the insertion angle of the fascicles (pennation angle) in aponeurosis strongly influence it (Aagaard et al., 2001). Therefore, an increase in PA is commonly observed as response to resistance training (Aagaard et al., 2001; Gondin, Guette, Ballay, & Martin, 2005; Kanehisa et al., 2002; Kawakami et al., 1995; Matta et al., 2011; Narici, 1999) (Figure 1). An increase in FL as chronic response to resistance training is also reported by some authors (Alegre, Jiménez, Gonzalo-Orden, Martín-Acero, & Aguado, 2006; Blazevich, Cannavan, et al., 2007; Narici et al., 2011; Potier, Alexander, & Seynnes, 2009; Reeves et al., 2004; Seynnes et al., 2007). Because the total distance shortened by a muscle fiber results from the product of each sarcomere displacement by the number of sarcomeres (Narici, 1999) an increase in FL is expected to enable for a greater contraction velocity (Burkholder, Fingado, Baron, & Lieber, 1994; Lieber & Fridén, 2000, 2001; Narici, 1999).

Therefore, there is a tendency for a functional adaptation on muscle architecture to load characteristics of the training program. While high velocity of shortening protocols leads to an increases on FL (Alegre et al., 2006; Blazevich et al., 2003), high load/low velocity protocols lead to greater increase on PA and muscle size (Aagaard et al., 2001; Blazevich & Giorgi, 2001; Gondin et al., 2005; Kawakami et al., 1995; Matta et al., 2011; Narici et al., 2011; Reeves et al., 2004; Seynnes et al., 2007). Therefore, adaptation of muscle architecture parameters seems to be dependent on the velocity (Alegre et al., 2006; Blazevich et al., 2003), type of contraction (Blazevich, Cannavan, et al., 2007; Franchi et al., 2014), range of motion (McMahon et al., 2013), duration of the training protocol and training background of the subjects

(Rønnestad, Kojedal, Losnegard, Kvamme, & Raastad, 2011). The majority of interventions studies on muscle architecture used isotonic training. Also isokinetic (Baroni et al., 2013; Blazevich, Cannavan, et al., 2007; Blazevich, Gill, Deans, & Zhou, 2007) or non-gravity-dependent equipment (Seynnes et al., 2007) has been used. The differences on the mechanical load characteristics induced by the equipment seems to have an important role in the observed results (Franchi et al., 2014). Particularly on isokinetic studies, the type of contraction and the preset dynamometer velocity seem to lead to different adaptations or magnitude of those. Concentric only (Blazevich, Cannavan, et al., 2007), eccentric only (Baroni et al., 2013; Blazevich, Cannavan, et al., 2007) or concentric/eccentric contractions protocols (Blazevich, Gill, et al., 2007) can be observed in scientific literature. In our best knowledge, only low isokinetic velocities as 30º/s (Blazevich, Cannavan, et al., 2007) or 60º/s (Baroni et al., 2013; Blazevich, Gill, et al., 2007) have been used in muscle architecture literature. Together with the type and isokinetic velocity of contraction, also the duration and volume (sets x reps) of the intervention difficult the comparison of results between the few muscle architecture studies that used such equipment. Because fascicles geometry adaptations, essentially fascicle length (McMahon et al., 2013), are sensible to training range of motion (ROM), higher muscle excursions (~90-100º) in comparison to those observed on everyday routine were used on isokinetic studies (Baroni et al., 2013; Blazevich, Cannavan, et al., 2007; Blazevich, Gill, et al., 2007).

While the effects of training with either high or low loads have been studied (Aagaard et al., 2001; Alegre et al., 2006; Blazevich et al., 2003; Kawakami et al., 1995; Reeves et al., 2004; Seynnes et al., 2007), to our best knowledge no other study examined changes in muscle size and architecture parameters to more functional training programs (wider range of training velocities). Moreover, in our best knowledge, only two other studies analyzed the effect of ROM on muscle size and fascicle arrangements on lower body. However, in both studies there was no equalization of training volume between training groups. In our study training volume was equalized between the full and partial ROM, allowing us to better understand the influence of ROM on muscle adaptation.

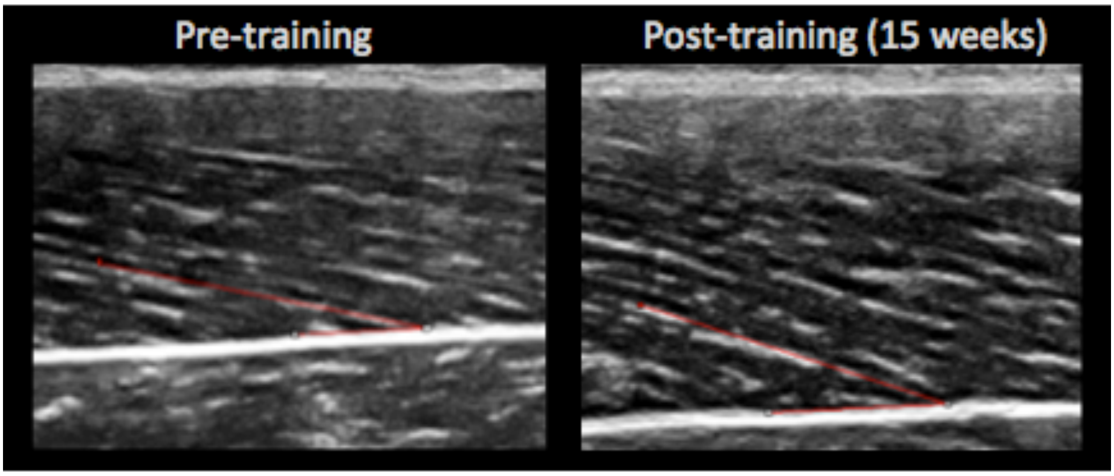

Figure 1. An example of changes in pennation angle from pre (13.7º) to post-training (20.4º).

1.2. Purpose of the study

The main purpose of the present study was to investigate changes in muscle size, fascicle geometry and knee extension maximal torque, induced by concentric isokinetic training with different range of motion. In more detail, our research questions were:

1- Does different range of motion isokinetic training exercises influences changes in muscle size?
2- Is there a heterogeneous hypertrophy on VL adaptation to isokinetic range of motion training?
3- Are changes in fascicle geometry mediated by different range of motion isokinetic training exercises?
4- Does different range of motion isokinetic training exercises influences knee extension maximal torque?

The present study is part of a larger research project on Strength Training and Muscle Architecture, which is the PhD work of Drª. Maria João Valamatos. The present study have only analysed a limited number of variables (muscle size, pennation angle and maximal isometric torque) and the effects of one single experimental condition (concentric contraction).

1.3. Relevance of the study

Longitudinal and transversal studies concerning muscle size and architecture can be found in the literature. Transversal studies demonstrate the existent relationships between muscle size, fascicle geometry and performance (Abe, Fukashiro, Harada, & Kawamoto, 2001; Abe, Kumagai, & Brechue, 2000; Kawakami et al., 1993; Kumagai & Abe, 2000; Maughan, Watson, & Weir, 1984). Examples are the observed correlations between muscle size and maximum force (Maughan et al., 1984) and FL and sprint performance (Abe, Fukashiro, Harada, & Kawamoto, 2001; Kumagai et al., 2000), or the greater PA observed in bodybuilders in comparison to untrained subjects (Kawakami et al., 1993) and the greater FL verified in professional sprinters when compared to distance runners (Abe, Kumagai, & Brechue, 2000). On other hand, longitudinal studies concerned on comparing the influence of different training variables on muscle size and architecture adaptation (Aagaard et al., 2001; Blazevich & Giorgi, 2001; A. Blazevich, Cannavan, et al., 2007; McMahon et al., 2013). These adaptations on PA, FL and muscle size have been suggested to be dependent of a number of training variables. Additionally, strength training background of the subjects, have been reported as an important influencing factor (Rønnestad et al., 2011). The training velocity (Alegre et al., 2006; Blazevich et al., 2003), the type of muscle contraction (Blazevich, Cannavan, et al., 2007; Franchi et al., 2014) and more recently the range of motion (McMahon et al., 2013) of training exercises, are examples of some training variables that can influence how the skeletal muscle structurally adapts to resistance training. Generally, when subjects are exposed to very high loads stimulus (e.g. strength training), muscle size and PA tends to increase (Aagaard et al., 2001; Kawakami et al., 1995; Reeves et al., 2004; Seynnes et al., 2007). Contrariwise, when the loads are smaller allowing for higher contraction velocities, increases on muscle length and FL are expected (Alegre et al., 2006; Blazevich et al., 2003). Controversial results have been reported in the literature concerning the type of contraction, with eccentric training demonstrating lower (Franchi et al., 2014), or greater (Blazevich, Cannavan, et al., 2007) increases in PA when compared to concentric training. Differences on the type of training (isotonic vs. isokinetic) can be responsible for this distinct finding (Franchi et al., 2014). Also non-significant differences in FL between concentric and eccentric groups were found in the study of Blazevich, Cannavan, et al. (2007), whereas a greater increase in eccentric training in comparison to concentric training was reported by Franchi et al. (2014). A higher magnitude of increase on FL was reported by Potier et al. (2009) as a result of 8 week of eccentric training in comparison to those who trained eccentrically in the studies of Blazevich, Cannavan, et al. (2007) and Franchi et al. (2014) (respectively 33,5% vs. 3,1% vs. 12%). The authors explained such differences in the magnitudes as the specificity of the studied muscle (i.e. biceps femoris vs. vastus lateralis). Different magnitudes and controversial results on the adaptations of the PA and FL have been reported in literature. This can be attributed to the characteristics of the training protocols (volume, training intensity or duration of the intervention) (Blazevich, Cannavan, et al., 2007; Blazevich, Gill, et al., 2007) the type of equipment used (e.g. isokinetic, isotonic, etc.) (Blazevich, Cannavan, et al., 2007; Franchi et al., 2014) or the studied muscle (Blazevich, Cannavan, et al., 2007; Potier et al., 2009).

In our best knowledge only two studies have analyzed muscle architecture (both VL) adaptations to differences in ROM (Bloomquist et al., 2013; McMahon et al., 2013). Both authors reported no differences in PA between ROM interventions (Bloomquist et al., 2013; McMahon et al., 2013). Fascicle length was only measured on the study of McMahon et al. (2013). The authors verified greater significant increases on all measured regions (25, 50 and 75%) in both training groups (large and short ROM group) with the larger ROM group demonstrating higher increases in FL measured at 50 and 75% of total muscle length. Therefore the authors concluded that differences on training ROM are responsible for specific adaptions on FL along muscle length. Previous studies analyzed the effect of ROM using either free weights, machines and bodyweight exercises (McMahon et al., 2013) or squat only exercise (Bloomquist et al., 2013). A more controlled approach (single-joint exercise) might advised to better address the influence of ROM on muscle structure adaptation. Therefore, we have choosen a single-joint exercise (knee extension) as the only exercise of our training intervention. Moreover, given the force-length and force-velocity relationship we trained the subjects on an isokinetic dynamometer so these two variables do not interfere with our findings. In previous research of muscle architecture and muscle size adaptation to ROM interventions, the training volume was not equalized (Bloomquist et al., 2013; McMahon et al., 2013) between groups. In the present study, training volume was equalized between training groups (full vs. partial ROM) using time under tension (TUT). This allowed us to have greater certainty that any differences between groups resulted from the manipulation of the range of motion.

1.4. Assumptions and Limitations

The most important assumptions of this study were:

- In the beginning, all subjects were physically active but had no experience in regular and systematic strength training on the 6 months before the beginning of the present study;
- Exclusion criteria of this study included the presence of any muscular or orthopedic pathology on the lower body;
- Subjects performed no additional lower body resistance training during the training intervention;
- An attendance of at least 90% of the planned number of sessions, without missing twice in a row, was a requirement for the maintenance of the participants on the present study;
- In order to do not conflict with the intervention, the period of adaptation to the isokinetic exercise used for training was sufficient for subjects acquire the necessary technique.

As it happens with the majority of the studies, especially when the experimental design includes a training intervention, the more relevant limitations of the present study were:

- Difficulties were found on PA observation of VL in a proximal and distal region. Therefore, data from both regions were not included in the present study;
- In order to better understand how VL adapts during the 15 weeks of training, it would have been interesting to have intermediate measures of muscle size, PA and knee extension maximal torque;
- The fact that fascicle length was not assessed in the present study limits our understanding on how VL adapts structurally to ROM training.

- Given the heterogeneous hypertrophy of quadriceps muscle group to resistance training, our findings on VL may not reflect whole muscle group adaptation.

2. Review of literature

2.1. Skeletal muscle structure

Structural adaptations in skeletal muscle are expected as response to strength training. These have been assessed at different levels ranging from microscopic – muscle fiber (Aagaard et al., 2001; Akima et al., 1999; Andersen & Aagaard, 2000; Hikida et al., 2000; Sharman et al., 2001; Staron et al., 1994; Volek et al., 1999) to macroscopic evaluation – muscle size (Aagaard et al., 2001; Kawakami et al., 1995; Matta et al., 2011; Rutherford & Jones, 1992; Starkey et al., 1996). Through muscle resections by biopsies researchers can evaluate some properties of the muscle cell. Although quite detailed, this technique presents a clear difficulty, which is the level of intrusion necessary to obtain the sample of the tissue. Also, the analysis of the sample obtained can be erroneuos given the heterogeneus adaptations observed on different muscle regions (Blazevich et al., 2003; Häkkinen et al., 2001; Housh et al., 1992; McMahon et al., 2013; Narici, Hoppeler, et al., 1996; Reeves et al., 2004). On the other hand, techniques that analyze muscle size (i.e. MT, PCSA, ACSA, muscle volume) are less intrusive. As we will see later in this literature review, the various existing techniques provide information with different level of accuracy and interest to researchers. Therefore some caution is recommended when comparing the results obtained by different techniques. Given its determinant role in muscle contraction, also the organization of the contractile material within the muscle has gained greater consideration by researchers. This arrangement of the fascicles is usually termed muscle architecture or fascicle geometry (Kawakami et al., 1995; Lieber & Fridén, 2000, 2001; Mairet, Maïsetti, & Portero, 2006).

2.1.1. Muscle architecture definitions

In the Human skeletal musculature there are as many different architectural arrangements as the number of muscles (Lieber & Fridén, 2000, 2001). Roughly, there can be distinct two main classes of skeletal muscles according to the arrangement of their fibers: the fusiform or parallel muscles (e.g. biceps brachii) whose fibers are oriented in parallel to the line of action of the muscle (Jones, Rutherford, & Parker, 1989; Narici, 1999) and the pennate muscles where fibers insert in the aponeurosis with a certain angle to the line of tension (Jones et al., 1989; Kawakami et al., 1995; Kawakami, Ichinose, & Fukunaga, 1998; Narici, 1999). Pennate muscles can be further divided into unipennate muscles (e.g. semi-membranous) and multipennate muscles (e.g. deltoid) depending respectively if muscle fibers insert in aponeurosis at a single or several angles (Lieber & Fridén, 2000, 2001). As we will see later, this angle that characterize the pennate muscles, has a determining role in muscle function.

Normally included measurements of muscle architecture are: pennation angle, wich is the angle measured between the fascicle and deep aponeurosis; and fascicle length (Abe et al., 1999; Kawakami et al., 1993; Kumagai et al., 2000; Nimphius et al., 2012). Given the close relation with the muscle structure, these two parameters are usually related to one or more indicators of muscle size, as physiological/anatomical cross-sectional area or muscle thickness (Aagaard et al., 2001; Blazevich, Cannavan, et al., 2007; Blazevich, Gill, et al., 2007; Reeves et al., 2004). Figure 2 shows an image obtained through ultrasonography where PA, FL and MT can be distinguished.

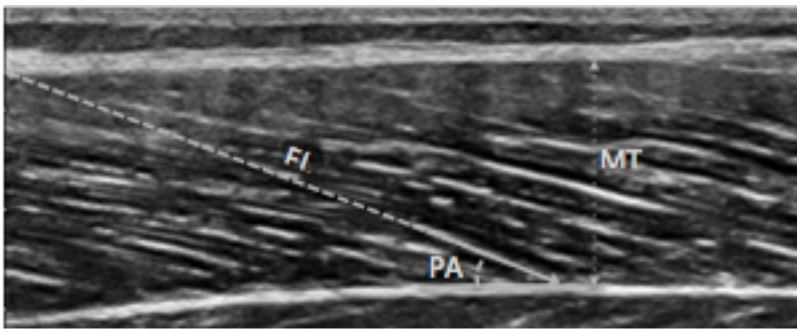

Figure 2. A sonograph of vastus lateralis with architectural parameters.

2.2. Measuring of muscle structure

2.2.1. Muscle architecture measurement

Historically, the architecture of skeletal muscle has been described using data obtained in directed dissection of cadavers (Friederich & Brand, 1990; Lieber et al., 1990; Wickiewicz et al., 1983). However, studies *in vitro* can have some issues like the shrinkage from maceration, the limited number of fibers that are measured which may not be representative of the muscle, or the fragility of some fibers from certain muscles (Friederich & Brand, 1990). Rutherford & Jones (1992) also suggest that some changes in the angle of the fibers might be expected due the process of fixation. Other limitation of the *in vitro* measuring is the obvious inability to study the effect of muscle contraction or changes in the joint position in muscle architecture, which are known to change even during isometric actions (Fukunaga, Ichinose, Ito, Kawakami, & Fukashiro, 1997; Kawakami et al., 1998; Muramatsu, Muraoka, Kawakami, Shibayama, & Fukunaga, 2002; Narici, Binzoni, et al., 1996).

Progress in technology, such as ultrasonography (Aagaard et al., 2001; Abe et al., 2001; Blazevich & Giorgi, 2001; Blazevich, Cannavan, et al., 2007; Kawakami et al., 1995, 1998; Narici, Binzoni, et al., 1996; Rutherford & Jones, 1992) or magnetic resonance imaging (Aagaard et al., 2001; Kawakami et al., 1995; Narici, Binzoni, et al., 1996) allowed to measure the architectural parameters *in vivo,* both at rest (Aagaard et al., 2001; Alegre et al., 2006; Blazevich & Giorgi, 2001; A. Blazevich, Gill, et al., 2007; Gondin et al., 2005; Kawakami et al., 1995; Matta et al., 2011; Narici et al., 2011) and during contraction (Fukunaga, Ichinose, et al., 1997; Kawakami et al., 1998; Muramatsu et al., 2002; Narici, Binzoni, et al., 1996). Since ultrasound is a minimally invasive, viable method and not expensive, it has been widely used in the literature (Kawakami et al., 1993; Narici, Binzoni, et al., 1996). To check the accuracy of the US technique, Narici, Binzoni et al. (1996) Compared ultrasound-determined muscle architecture with direct measurement. The authors found no significant differences in PA, FL and MT, concluding that a good agreement exists between both techniques. Also, Kawakami et al. (1993) found no major differences in US measurements and manual measurements on three human cadavers in both MT (0-1 mm) and PA (0-1º). Therefore, viable measures can be expected when using ultrasonography to determine muscle architecture parameters.

2.2.1.1. Measuring of fascicle length

The length of a fascicle is measured from aponeurosis to aponeurosis and can be obtained directly using longitudinal ultrasonic images as seen in Figure 2 (Fukunaga, Ichinose, et al., 1997; Kawakami, Abe, Kanehisa, & Fukunaga, 2006; Kawakami et al., 1998). However, because sometimes the fascicles are too long to be observed directly, its length has been estimated through equations (Fukunaga et al., 2001; Kawakami et al., 1995; Kumagai et al., 2000; Mairet, Maïsetti, & Portero, 2006; Nimphius et al., 2012) or extrapolating from the identifiable end of a fascicle to a line drawn from the superficial aponeurosis (Blazevich, Cannavan, et al., 2007; Narici, 1999; Potier et al., 2009; Reeves et al., 2004). Normally the equation used for the estimation of FL is a trigonometric equation: FL = MT $(\sin \theta)^{-1}$, where θ is the fascicle angle between the fascicle and deeper aponeurosis (Fukunaga et al., 2001; Kawakami et al., 1995; Kumagai et al., 2000; Nimphius et al., 2012). The average of the PA measured using superior and deep aponeurosis can also be used. However, no different results using one or other method seems to exist (Mairet et al., 2006). Although this method is widely used in literature, caution must be taken when estimating FL through either extrapolation or equation as fascicles might have a curvilinear aspect (Kawakami et al., 1993, 1995; Muramatsu et al., 2002). Since the sonograms results from the echo of the emitted ultra-sound reflex, a different placing of the probe can also give erroneous measurements. Moreover, differential longitudinal or transversal collocation of the probe in different occasions can display different regions of the muscle. Being that, it's strongly recommended that the technician is well trained handling the probe and the chosen locations for observation are mapped both longitudinally and transversely (Blazevich, Cannavan, et al., 2007; Blazevich, Gill, et al., 2007).

2.2.1.2. Measuring of pennation angle

As aforementioned, in the pennate muscles the fascicles inserts in the aponeurosis with a certain angle, thus they are arranged obliquely to the line of force production (Jones et al., 1989; Kawakami et al., 1995, 1998; Narici, 1999). This angle (PA), which can be measured through ultrasonography as the angle between deep aponeurosis and the fascicles (Abe et al., 1999; Kawakami et al., 1993; Kumagai et al., 2000; Nimphius et al., 2012), allows more contractile material to be attached in a given area (Jones & Rutherford, 1987; Kawakami et al., 1995; Lieber & Fridén, 2001). Being that, a positive correlation between the fascicle angle and muscle size measured as the anatomical cross-sectional area (Rutherford & Jones, 1992), muscle thickness (Fukunaga, Kawakami, Kuno, Funato, & Fukashiro, 1997; Kawakami et al., 1993, 2006, 1995; Kubo et al., 2003) and muscle volume (Aagaard et al., 2001), can be observed. Some authors however found no correlations (Alegre et al., 2006; Kearns, Abe, & Brechue, 2000) between MT and PA. The relationship between MT and PA seems to be dependent on different muscles and populations used for study (Kearns et al., 2000).

2.2.2. Measuring of muscle size

In literature, muscle size has been measured through differents methods (i.e. PCSA/ACSA, MT, muscle volume) with authors using one (Kawakami et al., 1993, 2006, 1995; Rutherford & Jones, 1992) or more (Aagaard et al., 2001; Fukunaga et al., 2001) techniques. Muscle thickness, is the perpendicular distance between the superficial and deep aponeurosis (Figure 2) and can also be obtained through ultrasonography (Abe et al., 1999, 2001; Kawakami et al., 1993; Kumagai et al., 2000; Mairet et al., 2006). This technique is held to be accurate, reproducible (Kawakami et al., 1993; Narici, Binzoni, et al., 1996), and it is regarded to have highly significant correlations with muscle anatomical cross-sectional area, which is a good indicator of muscle size (Martinson & Stokes, 1991). Also ACSA and PCSA are commonly used to determine muscle size, however some considerations must be taken in order to use one or the other measure of muscle size (Aagaard et al., 2001; Fukunaga et al., 1996; Fukunaga et al., 2001; Rutherford & Jones, 1992). Because the maximal force that skeletal muscle is capable to generate is proportional to the number of sarcomeres arranged in parallel (Gans & De Vree, 1987; Jones & Rutherford, 1987; Narici, 1999), the PCSA which include all the muscle fibers at right angles to their long axes (Fukunaga et al., 1996; Kawakami et al., 1995; Narici, 1999), seems to be the most precise method of assessing muscle size in relationship to muscle force (Aagaard et al., 2001; Lieber & Fridén, 2000). Therefore higher correlations were found between force and PCSA than force and ACSA (Aagaard et al., 2001; Fukunaga et al., 1996; Fukunaga et al., 2001). Nevertheless strong correlations do exist between ACSA and force (Aagaard et al., 2001; Fukunaga et al., 1996; Fukunaga et al., 2001; Maughan, Watson, & Weir, 1984).

Because it is impossible to measure all CSA fibers directly, the PCSA has been obtained from biopsy samples of the muscle (Aagaard et al., 2001) or estimated through formulas (Blazevich, Cannavan, et al., 2007; Fukunaga et al., 1996; Fukunaga et al., 2001; Kawakami et al., 1994, 1995; Reeves et al., 2004). In order to predict the PCSA is necessary to determine muscle volume, fascicle length and in case of pennate muscles the pennation angle (Blazevich, Cannavan, et al., 2007; Fukunaga et al., 1996; Fukunaga et al., 2001; Kawakami et al., 1994, 1995; Reeves et al., 2004). Muscle volume can be calculated by summing the various slices of ACSA along muscle length, obtained through MRI (Blazevich, Cannavan, et al., 2007; Fukunaga et al., 2001; Kawakami et al., 1994, 1995) or US (Reeves et al., 2004) and multiplied by the interval of each slice thickness (Reeves 2004; Kawakami 1995; Kawakami 1994). PA and FL can be measured by US and together with volume, PCSA can be determined: PCSA = Volume x cos θ x FL^{-1} (Blazevich, Cannavan, et al., 2007; Fukunaga et al., 2001, 1996; Kawakami et al., 1994, 1995).

On the other hand ACSA can be measured directly using MRI. Authors normally chose to use a single or several slices along whole muscle length (Blazevich, Cannavan, et al., 2007; Carey Smith & Rutherford, 1995; Häkkinen et al., 2001; Housh, Housh, Johnson, & Chu, 1992; Narici, Hoppeler, et al., 1996; Reeves et al., 2004). When using a single slice to represent muscle size, normally authors chose the one located at half distance of the muscle (Aagaard et al., 2001; Alegre et al., 2006; Blazevich & Giorgi, 2001; Blazevich, Cannavan, et al., 2007; Gondin et al., 2005; Narici et al., 2011), or the one that corresponds to the maximum CSA (Kanehisa et al., 2002; Kawakami et al., 1995). When one image is chosen to represent muscle size, careful must be taken because an heterogeneous hypertrophy as been demonstrated in some muscles (Blazevich, Cannavan, et al., 2007; Blazevich et al., 2003; Carey Smith & Rutherford, 1995; Häkkinen et al., 2001; Kawakami et al., 1995; Matta et al., 2011; Reeves et al., 2004; Seynnes et al., 2007), but not in others (Blazevich, Cannavan, et al., 2007; Matta et al., 2011; Reeves et al., 2004). Therefore, in some muscles (e.g. triceps brachii) CSA from a single slice seems to reflect the increases in whole muscle size (Kawakami et al., 1995; Matta et al., 2011). Specifically in the quadriceps muscles, an heterogeneous hypertrophy in the muscles along their lengths have been observed (Blazevich, Cannavan, et al., 2007; Blazevich et al., 2003; Carey Smith & Rutherford, 1995; Häkkinen et al., 2001; Housh et al., 1992; Narici, Hoppeler, et al., 1996; Reeves et al., 2004; Seynnes et al., 2007). Thus, when the objective is to verify the adaptations in muscle size, heterogeneous hypertrophy should be taken into account.

It seems that different usage of muscle size measures may lead to misleading conclusions about the size of the muscle and the force produced. This can be demonstrated by the disproportionate strength increases in comparison to some muscle size measures (ACSA) but not others (PCSA) (Aagaard et al., 2001). Although ACSA, PSCA, MT or muscle volume reflect muscle size and can be used to evaluate the adaptations to resistance training, when the objective is to assess the characteristics or functional adaptations with relation to muscle size (i.e. Specific force – muscle force.$PSCA^{-1}$; Kawakami et al., 1994, 1995), the use of PSCA appears more coherent since stronger correlations exist for PSCA and force than for ACSA and force (Fukunaga et al., 2001, 1996; Narici, 1999). As discussed, this can be observed beacause PCSA accounts with some parameters (i.e. arrangement of the fascicles) that strongly influenciate force production (Aagaard et al., 2001; Lieber & Fridén, 2000).

2.3. Functional implications of skeletal muscle architecture

Parameters of muscle architecture have been extensively studied with regard to muscle function, such as the ability to produce force (Lieber & Fridén, 2000, 2001). These architectural parameters are known to play an important role in the muscle function (Abe et al., 2001; Kawakami et al., 1994, 1993; Kumagai et al., 2000) even greater than the biochemical proprieties of the muscle cells (Burkholder, Fingado, Baron, & Lieber, 1994; Lieber & Blevins, 1989), and appear to be specialized according to their function (Lieber & Fridén, 2000, 2001; Wickiewicz et al., 1983). Generally, muscles with larger pennation angles and/or shorter fascicles appear to be more able to produce high values of force (Kawakami et al., 1993; Lieber & Blevins, 1989; Lieber & Fridén, 2000, 2001), while muscles with smaller pennation angles and/or longer fascicles are more likely to produce force with higher velocity of contraction (Lieber & Fridén, 2000, 2001). Since larger pennation angles allow a great number of sarcomeres in parallel (Jones & Rutherford, 1987; Kawakami et al., 1993, 1995; Lieber & Fridén, 2001; Rutherford & Jones, 1992), and knowing that force is proportional to the amount of contractile material arranged in parallel (Gans

& De Vree, 1987; Jones & Rutherford, 1987; Narici, 1999), an increase in pennation angle is expected to be accompanied by an increase in force (Aagaard et al., 2001; Fukunaga et al., 2001; Narici, 1999). However, since the fascicles insert obliquely in the aponeurosis only part of the force produced by the fibers (fiber force x cos θ) will be actually transferred to the tendon (Blazevich, 2006; Gans & Gaunt, 1991; Kawakami et al., 1995; Lieber & Fridén, 2001; Maughan et al., 1984; Narici, 1999; Rutherford & Jones, 1992). Although, this effect is minimal in muscles with moderate pennation angles (Blazevich, 2006; Lieber & Fridén, 2001), such as those observed in human cadavers dissection (Friederich & Brand, 1990; Lieber et al., 1990; Wickiewicz et al., 1983). For example, a muscle with the fascicles oriented at a 30º angle to force-generation axis, would only transmit a portion (87%) of their force as: tendon force = muscle force x cosine 30º = 0,87 force produced (Lieber & Fridén, 2001).

Since fibers of the pennated muscles rotate during contraction (Fukunaga et al., 1997; Gans & Gaunt, 1991; Kawakami et al., 1998), increases in the pennation angle allow a greater tendon excursion for a given length of fiber shortening (Muhl, 1982). This rotation of pennate muscle fibers also allow a lower velocity of fiber shortening for a given muscle shortening velocity, which results in increased capacity for force production given the length-tension (Blazevich & Giorgi, 2001; Blazevich et al., 2003; Blazevich, Gill, & Zhou, 2006; Gans & Gaunt, 1991; Muhl, 1982) and force-velocity proprieties of the muscle (Blazevich & Giorgi, 2001; Blazevich et al., 2003, 2006; Kawakami et al., 1993).

If in one hand PA is closely related to the production of high values of force, on the other fascicle length has a major contribution on the velocity of contraction. Therefore, there is a good agreement in the proportionality of a sarcomere length and its shortening velocity, where longer fascicles are associated with an increased contraction velocity (Burkholder et al., 1994; Lieber & Fridén, 2000, 2001; Narici, 1999). This is easily understandable because the total distance shortened by a fiber results from the product of each sarcomere displacement by the number of sarcomeres (Narici, 1999). In a study from Kumagai et al. (2000), the authors schematically presented the differences in the contraction velocity of two muscles with different fascicles length (8.07 and 6.55 cm). On their model, the authors assumed a muscle shortening of about 10% of the fascicle length and a 250-ms duration of the muscular shortening. The shorter fascicle (6.55 cm) would shorten approximately 0.66 cm which results in a tendon excursion of 0.68 cm and a muscle shortening velocity of 2.72 cm/s. The longer fascicle (8.07 cm) would shorten 0.81 cm resulting in a tendon excursion of 0.83 cm and a muscle shortening velocity of 3.31 cm/s. Therefore, contraction of a muscle with longer fascicles will result in greater tendon excursion for the same relative shortening of each sarcomere, or in other words, a greater velocity of muscle shortening (Blazevich et al., 2006; Kumagai et al., 2000; Lieber & Fridén, 2001; Narici, 1999). Also, because for a muscle shortening at a given velocity the individual sarcomeres of a longer fiber (i.e. with more sarcomeres in series) has a slower contraction velocity, it allows the fiber to operate in a advantageous situation on its force-velocity curve (Lieber & Fridén, 2000, 2001)

2.4. Influence of range of motion on resistance training

Range of motion is one of the training variables that should be taken into account when designing resistance-training programs. Manipulation of ROM had been suggested for specific performance goals, as the usage of half squats for short sprints or quarter squats for maximum sprints (Young, Benton, Duthie, & Pryor, 2001) or partial amplitude bench press when seeking for increases on peak force and/or decreasing on deceleration at the end range of the movement (Clark, Bryant, & Humphries, 2008). Regarding this, both acute (Clark et al., 2008; Clark, Umphries, Ohmann, & Bryant, 2011; Mookerjee & Ratamess, 1999) and chronic responses (Bloomquist et al., 2013; Graves et al., 1992; Graves, Pollock, Jones, Colvin, & Leggett, 1989; Kubo et al., 2006; Massey & Vincent, 2004, 2005; McMahon et al., 2013; Pinto et al., 2012; Weiss, Fry, Wood, Relyea, & Melton, 2000) to training have been studied.

Regarding strength adaptations to different ROM interventions, controversial results have been found. While some authors report specific increases on the amplitude used for training (Bloomquist et al., 2013; Clark et al., 2011; Graves et al., 1989; Kubo et al., 2006; Massey & Vincent, 2005; McMahon et al., 2013; Pinto et al., 2012; Weiss et al., 2000) others do not observed such specificity (Graves et al., 1992; Massey & Vincent, 2004). The superiority observed in those who trained with a full (or larger)

ROM can partly be explained by greater increases in muscle size (e.g. CSA) (Bloomquist et al., 2013; McMahon et al., 2013). Differences on muscle size arising from ROM training are suggested to result from the greater stress and lengthening of the sarcomeres as result of training with or at a greater ROM (Kubo et al., 2006; McMahon et al., 2013). Specific adaptations on architectural parameters can also be found as chronic response to different ROM resistance training (Bloomquist et al., 2013; McMahon et al., 2013). Nevertheless, in our best knowledge none of the referred studies equalized training volume. Time under tension is well known to strongly influence muscle hypertrophy (Burd et al., 2012; Schoenfeld, 2010, 2013), therefore, training with greater amplitude for the same volume (sets and repetitions) will expose muscles to higher time under tension. Even that force production is higher when using lower ROM training, the increased displacement of the resistance results on a greater mechanical work (Clark et al., 2008). Being that, differences observed previously between ROM groups can be justified by differences in TUT rather then the manipulation of the training amplitude. Adaptations on muscle size and architectural parameter as response to ROM resistance training can be found in Table 1. An extensive understanding of muscle size and fascicle geometry adaptation concerning ROM resistance training can be found in the following chapters of this bibliographic revision.

2.5.Musculature plasticity to resistance training

It is well accepted that skeletal muscles are liable to adapt as a response to a mechanical stimulus (Aagaard et al., 2001; Alegre et al., 2006; Blazevich & Giorgi, 2001; Blazevich, Cannavan, et al., 2007; Gondin et al., 2005; Kawakami et al., 1995; Matta et al., 2011; Narici et al., 2011; Potier et al., 2009; Reeves et al., 2004; Rutherford & Jones, 1992). To address this, differences in architectural parameters have been investigated concerning to performance (Abe et al., 2001; Kumagai et al., 2000), differences between populations (Kawakami et al., 1993; Kearns et al., 2000) or as response to training (Aagaard et al., 2001; Blazevich, Gill, et al., 2007; Kawakami et al., 1995; Matta et al., 2011; Nimphius et al., 2012; Rutherford & Jones, 1992; Starkey & Pollock, 1996) and detraining (Blazevich, Cannavan, et al., 2007; Fukunaga et al., 2001). A summary of both architectural and muscle size adaptations to different types of resistance training can be seen in Table 2. Typically adaptations arising from resistance training are increases in pennation angle and muscle size (Aagaard et al., 2001; Gondin et al., 2005; Kanehisa et al., 2002; Kawakami et al., 1995; Matta et al., 2011; Narici, 1999). Also, an increases in FL as response to resistance training were reported by some authors (Alegre et al., 2006; Blazevich, Cannavan, et al., 2007; Narici et al., 2011; Potier et al., 2009; Reeves et al., 2004; Seynnes et al., 2007). Therefore, adaptation of muscle architecture parameters seems to be dependent on the velocity (Alegre et al., 2006; Blazevich et al., 2003), type of contraction (Blazevich, Cannavan, et al., 2007; Franchi et al., 2014), range of motion (McMahon et al., 2013), duration of the training protocol and training background of the subjects (Rønnestad et al., 2011).

2.5.1. Muscle size

Changes in muscle size are directly influenced by increases in muscle fiber size (hypertrophy) (Aagaard et al., 2001; Volek et al., 1999) and/or the arrangement of muscle fibers (or fascicles) within the muscle (Blazevich & Giorgi, 2001; Blazevich et al., 2003; Seynnes et al., 2007). While some authors attribute the increase in muscle size to the increase in FL (Baroni et al., 2013; Reeves et al., 2004), others attribute to an increase PA (Aagaard et al., 2001) or both FL and PA (Blazevich, Cannavan, et al., 2007). A scheme of differences on fascicles geometry adaptation leading to increases in MT can be observed on Figure 3. Increases in muscle size, measured as MT (Kawakami et al., 1995; Matta et al., 2011; Starkey et al., 1996), PCSA (Aagaard et al., 2001; Kawakami et al., 1995), ACSA (Aagaard et al., 2001; Kawakami et al., 1995; Rutherford & Jones, 1992) or muscle volume (Aagaard et al., 2001; Kawakami et al., 1995) has been shown to exist as an adaptation to training interventions. Moreover, physiological fiber area (hypertrophy) also increase as response to resistance training (Aagaard et al., 2001; Volek et al., 1999).

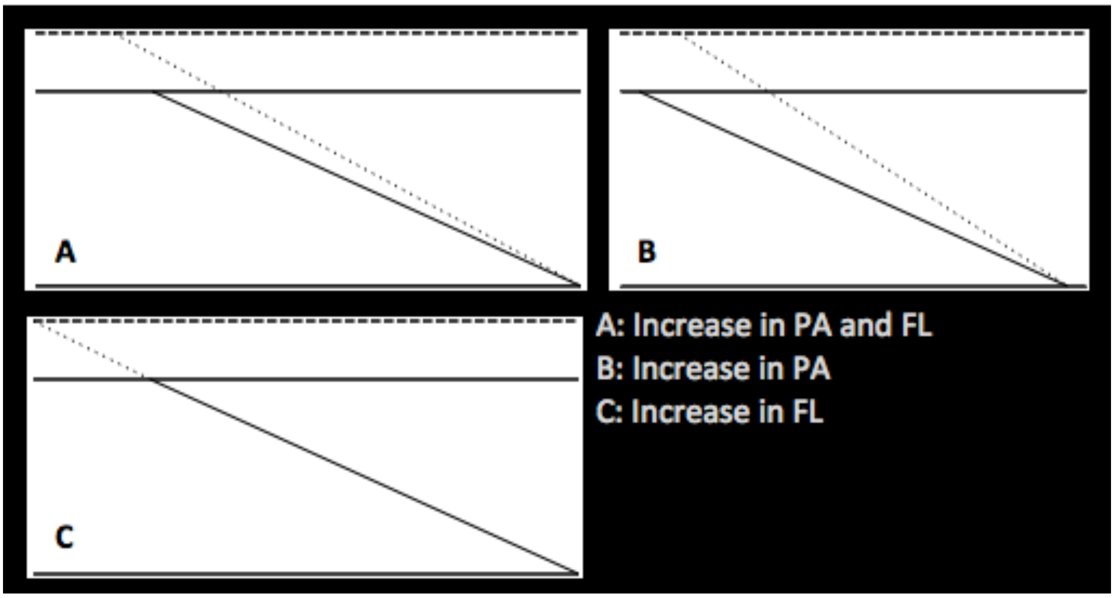

Figure 3. Different changes in FL and PA leading to similar increase in MT.

Hypertrophy of Human skeletal muscle fibers its well known to occur at the very beginning of a resistance training (Akima et al., 1999; Narici, Hoppeler, et al., 1996; Staron et al., 1994), and continue to increase until a plateau is reached as demonstrated by the inexistent of significant increases in more experienced individuals, as competitive weightlifters, powerlifers or bodybuilders (Hakkinen, Pakarinen, Alen, Kauhanen, & Komi, 1988; Häkkinen, Komi, Alén, & Kauhanen, 1987). Therefore, minor or absence of increases on muscle size are expected in subjects with greater training background (Ahtiainen, Pakarinen, Alen, Kraemer, & Häkkinen, 2003; Hakkinen et al., 1988; Häkkinen et al., 1987).

Differences on the onset of muscle size adaptations after training have been reported, where absence of early significant increases have been observed by some authors (Akima et al., 1999; Blazevich, Gill, et al., 2007), but not others (Baroni et al., 2013; Blazevich, Cannavan, et al., 2007; Seynnes et al., 2007; Tesch, Ekberg, Lindquist, & Trieschmann, 2004). Lack of early changes in muscle size can be attributed to the short duration of the intervention (Akima et al., 1999; Blazevich, Gill, et al., 2007), or differences on the training protocols (Blazevich, Cannavan, et al., 2007; Seynnes et al., 2007; Tesch et al., 2004). Akima et al. (1999) found no significant changes in CSA and fiber area of quadriceps femoris after 2 week of knee extension performed on isokinetic. Absence of early significant increases on MT were also found by Blazevich, Gill, et al. (2007) on the different portions of quadriceps muscle after 5 weeks of isokinetic knee extension (60º/s). However, Blazevich, Cannavan, et al. (2007) verified significant increases in MT of VL after 5 weeks (3 times per week) of isokinetic concentric and eccentric knee extension (30º/s). Muscle thickness of vastus medialis (VM) was also greater after training, although it was not enough to achieve a statistical significance. Because differential muscle hypertrophy within the same muscle group has been reported as response to a training program, it is possible for a muscle to achieve a significant increase but not the other (Blazevich, Cannavan, et al., 2007; Blazevich et al., 2003; Housh et al., 1992; Häkkinen et al., 2001; Narici, Hoppeler, et al., 1996; Seynnes et al., 2007). Lower isokinetic velocity is associated with greater time under tension and force (given the force/time relationship). Because both variables are known to be determinant for increases in muscle mass (Schoenfeld, 2010, 2013), the lower isokinetic velocity used by Blazevich, Cannavan, et al. (2007) in comparison to Blazevich, Gill, et al. (2007) (30º/s vs. 60º/s, respectively) may explain the observed differences on muscle size measured as MT. Similar findings were observed by Cormie, McGuigan, & Newton (2010) when comparing 10 weeks of either strength (75-90% RM) or power training (0-30% RM). While strength training (great time under tension and force) led to significant increases on MT of VL (after 5 and 10 weeks), power training led to no significant changes on MT. Nevertheless, Baroni et al. (2013), found significant increases in MT of VL and RF after 4 weeks of isokinetic eccentric training at the same velocity of Blazevich, Gill, et al. (2007) (60º/s). Methodological differences in the studies (i.e. 4 sets of 6 reps vs. 3 sets of 10 reps) are possible to be responsible for the observed differences between both studies. Also, Seynnes et al. (2007) and Tesch et al. (2004) found significant changes on quadriceps muscles size after a short-term intervention, during respectively 20 and 35 days. According to the authors, the early increases in muscle size might be obtained because of the type of resistance equipment (non-gravity-dependent – view Tesch et al., 2004 for further details) that allow for an eccentric overload in comparison to other type of equipment. This eccentric overload is associated with greater increases in muscle size (Farthing & Chilibeck, 2003; Higbie, Cureton, Warren, & Prior, 1996; Roig et al., 2009), and consequently more recommended when the goal is to increase muscle mass (Bird, Tarpenning, & Marino, 2005; Kraemer & Ratamess, 2004). Again, in both studies (Seynnes et al., 2007; Tesch et al., 2004) a heterogeneous hypertrophy on different portions of the same muscle group (quadriceps) was observed.

Beside the type of contraction (Blazevich, Cannavan, et al., 2007; Seynnes et al., 2007; Tesch et al., 2004) and the velocity/time under tension (Cormie et al., 2010), also the ROM seems to influenciate the adaptations on muscle size (Bloomquist et al., 2013; McMahon et al., 2013). Bloomquist et al. (2013) compaired the effect of 12 weeks of progressive squat training performed with either deep (0-120º of knee flexion) or shallow squat (0-60º of knee flexion). The authors verified significant increases in both groups on front thigh muscules CSA (m. sartorius, quadriceps and adductors in the most proximal sections), although no significant changes on MT of VL (measured 50% between the greater trochanter and the lateral condyle) were observed for both groups. When comparing between training groups, significant differences were found on all CSA slices but not on MT of VL. Therefore the authors conclude that increases on front thigh muscles CSA can be better explained by the increase of other muscles rather than VL. However, because heterogeneous muscle size adaptations on VL were previously observed (Blazevich et al., 2003; Häkkinen et al., 2001; Housh et al., 1992; McMahon et al., 2013; Reeves et al., 2004), it is possible that absence of increases on 50% do not reflect changes on muscle along it length. In fact, McMahon et al. (2013) found significant differences between small and large ROM group (0-50º and 0-90º of knee flexion, respectively) on VL ACSA measured at 75% of total femur length after 8 weeks of lower body inoinertial resistance training. However the authors found no differences between groups on the other two regions (25, 50%), concluding that the observed discrepancies in CSA between groups may be explained by the regional differences in the total stimulus (i.e. force generation and stretch) transmitted along the length of the muscle. In the elbow flexors, Pinto et al. (2012) observed significant increases on MT as adaptation to 10 weeks of strength training with either full or partial ROM. No differences between intervention groups were found. Nevertheless, none of the three studies that analyzed the influence of training ROM on muscle size equalized training volume between groups. Possible if the same training volume was equal between training groups, the observed differences verified in some of the muscle size measurements would not exist.

In conclusion, adding to the velocity (Cormie et al., 2010) and type of contraction (Blazevich, Cannavan, et al., 2007; Seynnes et al., 2007; Tesch et al., 2004) also the amplitude of the movement (Bloomquist et al., 2013; McMahon et al., 2013) seem to have a determinant role in the adaptation of muscle size and architecture.

2.5.2. Pennation angle

As mentioned before in this review, PA is expected to increase as a result of resistance training. However, different magnitudes of gains can be observed even within the same muscle. Analysing the adaptations on the pennation angle of the vastus lateralis in subjects who had never participated in any systematic training, Aagaard et al. (2001) verified significant increases (35.5%) after 14 weeks of progressive heavy-resistance strength training. Minor but significant increases (14%) where found by Gondin et al. (2005) after a 8 weeks (4x week) of isometric electromyostimulation and Reeves et al. (2004) (13%) after 14 weeks of isotonic exercise. In a short term study (5 weeks, 3x week), Seynnes et al. (2007) observed a significant increase of 9.9% as response to a bilateral knee extension using a gravity-independent flywheel ergometer. Not only in resistance training can be observed adaptations in PA, Narici et al. (2011) also found significant increases on PA of VL (3.4%) as result of 3.5 hours of alpine skiing sessions, (12 weeks, 2-3x week). The different magnitude in the adaptations of the PA can be attributed to the characteristics on training protocols (volume, training intensity or duration of the intervention) or the type of equipment used (e.g. isokinetic, isotonic, etc.).

Non significant changes were reported by some authors (Alegre et al., 2006; Blazevich, Cannavan, et al., 2007; Blazevich et al., 2003; Blazevich, Gill, et al., 2007; Potier et al., 2009; Rønnestad, Kojedal, Losnegard, Kvamme, & Raastad, 2011; Rutherford & Jones, 1992). As happens with the diminished (or absence) increases in muscle mass as the level of training increases, the changes in pennation angle appear to be sensitive to the training background, where minor or no changes in PA are expected to occur in more experienced individuals (Blazevich & Giorgi, 2001; Blazevich et al., 2003; Rønnestad et al., 2011; Rutherford & Jones, 1992). In well-trained individuals, Rønnestad et al. (2011) (Nordic combined athletes) and Rutherford & Jones (1992) (power event athletes) found no changes in PA for the VL after 12 weeks of strength training. Similar results were found by Blazevich & Giorgi, (2001) on triceps brachial lateralis after a 12 weeks training protocol (2 days per week with exercises targeting triceps) with well-trained individuals (minimum 3 days/week for at least 1 year), where no changes on PA were observed. Although, the authors reported an increase of 39.5% on PA in the training group (same protocol) plus testosterone administration, indicating that the use of testosterone may have been responsible for this significant increase in the pennation angle. Therefore, this lower adaptation responses observed in either pennation angle (Blazevich & Giorgi, 2001; Rutherford & Jones, 1992; Rønnestad et al., 2011) and muscle size (Ahtiainen et al., 2003; Hakkinen et al., 1988; Keijo Häkkinen et al., 1987), might be explained by previous adaptations in response to training stimulus as demonstrated by the greater PA an MT observed in both bodybuilders (Kawakami et al., 1993) and sumo wrestlers (Kearns et al., 2000) in comparison to control groups.

Absence of changes in the PA were also found in less trained individuals (Alegre et al., 2006; Baroni et al., 2013; Blazevich, Cannavan, et al., 2007; Blazevich, Gill, et al., 2007; Potier et al., 2009). Comparing the effects of eccentric (ECC) and concentric (CON) isokinetic training on muscle architecture, Blazevich, Cannavan, et al. (2007) found no significant changes on PA of VM in either ECC or CON groups. In VL the authors found no significant differences in PA for the CON group (13.3%, $p=0.06$), although the ECC group demonstrate significant increases (21.4%, $p=0.03$). The authors argued that adaptations in fascicle angle of different muscles exposed (i.e. VL and VM) to the same training stimulus are not always consistent, due to its role in the chosen exercise(s). Controversial results were reported in a recent study comparing the effects of ECC and CON training in the PA adaptation (Franchi et al., 2014). The authors found that PA increased significantly less in the ECC group in comparison to the CON group. Differences on the type of training (isotonic vs. isokinetic) can be responsible for this distinct finding of Franchi et al. (2014). Lack of changes on PA of VL, rectus femoris, vastus intermedius, and vastus medialis, were also observed by Blazevich, Gill, et al. (2007) resulting from a 5 weeks (3 times per week) of unilateral isokinetic knee extension. The subjects performed 4 sets of 6 reps for the first 2,5 weeks at a speed of 60º/second, increasing 1 set for the remaining weeks. Perhaps the stimulus was not sufficient to impose adaptations on PA, or the duration (5 weeks) was to short for any significant PA increases. Although, early (5 weeks) significant changes in PA were observed by others (Blazevich, Cannavan, et al., 2007; Seynnes et al., 2007). More controversial results were reported by Baroni et al. (2013) showing no significant changes in PA of VL and RF after 12 weeks of isokinetic eccentric knee extension. As discussed by the authors, the measurement error of the ultrasonography analysis may lead to erroneous significant changes observed in other studies. In the biceps femoris muscle, Potier et al. (2009) found no significant changes in PA after an 8-week eccentric training program with untrained subjects. After determining each subject RM, which consisted in resisting the load (eccentrically) for 5 seconds, the subjects then had to train 3 days per week during the 8 weeks with that previously obtained load (RM), with the goal of completing the maximum reps as possible for 3 sets. The information about the number of reps obtained (with the determined RM) at the end of the intervention was not revealed, and therefore it is impossible to determine the training volume, which might have been a restriction for increases in PA.

Alegre et al. (2006) verified small non-significant decreases in PA of VL as response to a 13 weeks (3 days per week) of low load resistance training program (30-60%RM of half squat lift) with male physical education students. According to the authors, the absence of increases in PA was due to the type of training that the subjects were exposed to (low intensity and high velocity), which resembles to speed training causing similar adaptations. In fact, Blazevich et al. (2003) found a significant decrease in a PA of VL (distally) as a result of 4 sprint/jump training sessions per week in a 5 week period. The PA of VL (proximally) and RF (distally) also decreased, despite no significant statistical differences were reported.

Contrary to what happens with MT, PA seem not to be influenced by the amplitude of the chosen exercises (Bloomquist et al., 2013; McMahon et al., 2013). After 12 weeks of squat training with a deep (0-120º of knee flexion) or shallow range of motion (0-60º of knee flexion), Bloomquist et al. (2013) found significant increases on PA of the VL measured 50% between the great trochanter and the lateral condyle. However the authors found no differences between groups. Similar results were found by McMahon et al. (2013) who found significant increases on PA of VL measured on three different sites (25, 50, 75% of total femur length) after 8 weeks of lower body inoinertial resistance training performed with either small or large ROM (0-50º and 0-90º of knee flexion, respectively). Again, although great average increase in the 3 measured sites, no significant differences between groups were found for pennation angle. It is important to refer that the training volume was not equalized in both studies, therefore this could be a possible explaination for the absence of significant differences between groups (Bloomquist et al., 2013; McMahon et al., 2013). In our best knowledge no other study investigated the influence of range of motion on pennation angle adaptions.

While moderate to heavy strength training appears to lead to an increase in the pennation angle and muscle size (Aagaard et al., 2001; Blazevich & Giorgi, 2001; Gondin et al., 2005; Kawakami et al., 1995; Matta et al., 2011; Narici et al., 2011; Reeves et al., 2004; Seynnes et al., 2007), training with lighter loads and consequently higher velocity appears to have no effect on increasing the pennation angle and may actually decrease it (Alegre et al., 2006; Blazevich et al., 2003). This decrease on PA associated with an increase on FL allows for higher speeds of contraction (Burkholder et al., 1994; Lieber & Fridén, 2000, 2001; Narici, 1999). Moreover, also the type of contraction seems to influence PA, where eccentric isokinetic training demonstrate greater increases on PA in comparison to concentric (Blazevich, Cannavan, et al., 2007). Lastly, minor or lack of influence of ROM is expected in PA adaptation to resistance training (Bloomquist et al., 2013; McMahon et al., 2013).

2.5.3. Fascicle length

Differences in fascicle length have been shown to exist between athletes and non-training subjects. Sumo wrestlers have significant greater FL for the triceps long head, vastus lateralis and gastrocnemius medialis than a control group (Kearns et al., 2000). Also, professional sprinters demonstrated to have greater fascicle lengths in comparison to a control group (Abe et al., 2001) or distance runners (Abe, Kumagai, & Brechue, 2000). Positive correlations were found between the fascicle length of the vastus lateralis and gastrocnemius lateralis, and professional sprinters 100-m their best record (Abe et al., 2001; Kumagai et al., 2000). Given this differences an important question can be raised, whether these differences are genetically imposed or result from a mechanical stimulus. In monozygous twins, Abe (2002) verified an interpair resemblance for FL, MT and PA of gastrocnemius lateralis, and for MT and PA of gastrocnemius medialis. No interperpair resemblance was found for FL of GM. The authors concluded that genetic predisposition is an important factor for fascicle length determination, however the absence of interpair resemblance for FL in GM may demonstrate that FL is influenced by other factors, such as mechanical stimulus, rather then genetic. Increases in FL, have been reported as adaptation to a training stimulus in Humans (Alegre et al., 2006; Narici, 1999; Potier et al., 2009; Reeves et al., 2004; Seynnes et al., 2007) and animals (Butterfield, Leonard, & Herzog, 2005; Lynn, Talbot, & Morgan, 1998) and appears to be dependent on the type of stimulus to which they are exposed, including speed of contraction (Alegre et al., 2006; Blazevich et al., 2003), type of contraction (Butterfield et al., 2005; Lynn et al., 1998) and range of motion (Burkholder, 2001; Koh & Herzog, 1998; McMahon et al., 2013).

The velocity of muscle shortening seems to influence the fascicle length adaptation, where an increase is expected as a chronic response to high-speed movements. Therefore, increases in fascicle length were observed after training with greater movement speed, such as jumps and running (Blazevich et al., 2003) or low load (30-60%RM) high speed resistance training (Alegre et al., 2006). The effect of eccentric training on addition of sarcomeres is controversial, where in animal studies some authors found increases in fascicle length (i.e. number of fascicles in series) (Butterfield et al., 2005; Lynn et al., 1998) but not others (Koh & Herzog, 1998). In Humans, Potier et al. (2009) analysed the effects of eccentric strength training on fascicle length of biceps femoris, verifying an increase of 34%. The authors speculate that such big differences to other studies might be because the specificity of each muscle. In our best knowledge, no other study assessed the effects of eccentric training in biceps femoris, making it difficult to compare results. Baroni et al. (2013) compared the effects of 12 weeks of isokinetic eccentric training on muscle architecture of VL and RF. Significant increases were reported by the authors on FL of both studied muscles (VL: 19.3%; RF: 16.7%). No significant differences between muscles were observed.

When comparing 10 weeks of leg press eccentric vs. concentric training, Franchi et al. (2014) have verified significant greater increases in FL of VL on the eccentric group (12%) vs. concentric group (5%). Absence of differences between eccentric and concentric training were reported by Blazevich, Cannavan, et al. (2007). Although the authors observed significant increases in FL (concentric: 6.3%; eccentric: 3,1%) after 10 weeks (3 times per week) of maximal isokinetic concentric and eccentric resistance in both groups in comparison to baseline. The authors concluded that others factors beside contraction mode may have influenced changes in fascicle length, especially the fact that training with higher range of motions (95-100º) than the habitual routine (e.g. walk, jogging or countermovement squat jump) may lead to a greater loading stimulus which resulting in an increase of fascicles length. This speculation is supported by the observed increase in sarcomere number as result of an increase in muscle excursion after a retinaculum transection of studied muscles, in rabbits (Koh & Herzog, 1998) and rats (Burkholder, 2001). Somehow, contradictory results were found by Blazevich et al. (2003) in Humans. The authors verified no significant changes in FL measured approximately at the same site of Blazevich, Cannavan, et al. (2007) on subjects who performed 5 weeks of a training program that consisted in 2 sessions of sprint/jump and 2 sessions of resistance training per week. The resistance training sessions consist in either barbell back squat to a 90º knee angle (SQ group) or unilateral forward hack squat to 110º internal knee angle (FHS group). Although, on a third group who performed 4 sessions of sprint/jump per week (SJ group) the authors reported a significant increase (80%) on FL of VL. The authors concluded that their findings on FL of VL were more related to the force and/or velocity characteristics of the exercises then with the movement patterns. Contradictory results were reported in the study of McMahon et al. (2013). After 8 weeks of lower body inoinertial resistance training performed with either small or large ROM (0-50º or 0-90º of knee flexion, respectively), the authors found greater significant increases on large ROM group at 50 and 75% of total femur length. Nevertheless, significant increases in FL on all measured regions (25, 50 and 75%) were found in both groups in comparison to baseline values. McMahon et al. (2013) concluded that differences on training ROM are responsible for different adaptions on FL along muscle length.

Like MT and PA, also contraditory results have been found regarding the time needed to observe significant changes in the length of the fascicles (Blazevich, Cannavan, et al. 2007; Blazevich, Gill, et al. 2,007; Seynnes et al. 2007). While Blazevich, Gill, et al. (2007) found no differences in the lengths of the fascicles after a 5 week intervention in all portions of the quadriceps, Blazevich, Cannavan, et al. (2007) found an increase in VL also after 5 weeks, being that no further changes were observed after 10 weeks. As discussed above, perhaps the difference in angular velocity was sufficient for these differences on the onset of fascicle length increase. Seynnes et al. (2007) found a significant increase in the length of the VL fascicles after only 10 days of training. The authors argued that these gains are due to the eccentric stimulus associated with the type of equipment used. Beyond the onset of the increases in the length of the fascicles, also the progress of increases over time is still unclear. Although some studies show an increase in fascicles after relatively long periods (Alegre et al., 2006; Narici et al., 2011; Reeves et al., 2004), the results cannot distinguish whether the increases in the length of the fascicles were linear or increased to a certain point and then stagnated or declined. In our best knowledge only a few studies (Blazevich, Cannavan, et al., 2007; Blazevich, Gill, et al., 2007; Seynnes et al., 2007) conducted intermediate assessments on the length of the fascicles in order to determine the progression of changes. As previously discussed, no changes were found by Blazevich, Gill, et al. (2007) after 2,5 or 5 weeks. Seynnes et al. (2007) verified an early increase on FL after only 10 days. After 20 and 35 days the FL continued to increase, although the authors only compared these values with the baseline. Also, Blazevich, Cannavan, et al. (2007) found an increase in the length of the fascicles of the FL after 5 weeks, whereas the remaining five weeks the authors found no significant differences. Thus it is possible that the fascicles quickly adapt to the stimulus and reach a plateau. This can be supported by Rønnestad et al. (2011) study, that showed no significant differences in the VL fascicle length after 14 weeks of strength training in well-trained Nordic combined athletes. According to the authors, the subjects possibly had already reached their potential for adjustments in the FL given their training background of several years training with explosive power methods, which as we saw earlier may be responsible for a greater fascicle length (Alegre et al., 2006; Blazevich et al., 2003). Kawakami et al. (1995) found no significant changes in FL of triceps brachii after 16 weeks of unilateral elbow extensors performed 3 times per week. The small number of subjects (n=5) and the chosen exercise "French press" may have contributed for the lack of significant changes in FL. In our best knowledge no other study analysed the effects of resistance training in FL of triceps brachii, therefore, no comparison is possible to be made. Changes in FL seem to be dependent on the studied muscle, where a heterogeneous adaptation on fascicle length within the same muscle (e.g. VL proximal or distal) or muscle group (e.g. VL or RF) can be observed (Blazevich et al., 2003). Moreover, also the training background (Rønnestad et al., 2011), duration of intervention (Blazevich, Cannavan, et al. 2007; Blazevich, Gill, et al. 2007; Seynnes et al. 2,007) and type of stimulus seem to influence adaptions in FL. Essentially the speed of contraction (Alegre et al., 2006; Blazevich et al., 2003), type of contraction

(Butterfield et al., 2005; Lynn et al., 1998) and range of motion (Burkholder, 2001; Koh & Herzog, 1998; McMahon et al., 2013) should be taken into account when seeking FL adapations.

Table 1. Muscle size and muscle architecture adaptations after ROM training

Study	Sample	Training	Studied muscles	Muscle Size	PA and FL
Bloomquist et al. (2013)	17 [9 shallow squat group (SS); 8 deep squat group (DS)] subjects non-enrollement in any strength and power sports	12 weeks; 3 days/wk 3-5 sets of 3-10RM of squat training with either deep (0-120º of knee flexion) or shallow (0-60º of knee flexion) ROM	Vastus Lateralis	Significant increase in CSA front thigh in the 6 measured sites (4-7%) on DS; Increase in CSA front thigh only in the two more proximal measured sites on SS (aprox 2-4%). Significant increase in the CSA back thigh of the second most proximal site in the DS group (aprox 3%). No significant changes in back thigh for SS.	Significant increase in PA on SS (23%) and DS (22%) group with no differences between groups
McMahon et al. (2013)	26 [8 short ROM group (SR); 8 long ROM group (LR); 10 control (Con)] recreationally active but never participated in a systematic strength training 12 months prior intervention	8 weeks; 3 days/wk 4 lower body exercises 3 sets of 10 (2 days) and 30 (1 day) reps with large (0-90º of knee flexion) or short (0-50º of knee flexion) ROM	Vastus Lateralis	VL ACSA significant increase in SR at 25 (16%), 50 (18%) and 75% (7%) of total femur length. VL ACSA significant increase in LR at 25 (25%), 50 (15%) and 75% (29%).	PA significant increases in SR at 25 (2%), 50 (4%) and 75% (11%) of total femur length. PA significant increases in LR at 25 (9%), 50 (7%) and 75% (11%). No differences were found between training groups. FL significant increase in measured sites (25, 50, 75% of femur length) in both training groups. Significant great increases in FL were found at 50 and 75% in LR in comparison to SR
Pinto et al. (2012)	40 [15 full ROM group (FULL); 15 partial ROM group (PART); 10 control group] no resistance training experience	10 weeks; 2 days/wk of bilateral preacher elbow flexion curl 2-4 sets of 20 to 8RM performed with either full (0-130º of elbow flexion) or partial (50-100º) ROM	Elbow Flexors	MT of elbow flexors increased significantly in both FULL (9,52%) and PART (7,37%) groups. No differences between group were found	Not assessed

Range of motion (ROM), repetition maximum (RM), cross-sectional area (CSA), anatomical cross-sectional area (ACSA), muscle thickness (MT), vastus lateralis (VL), pennation angle (PA), fascicle length (FL)

Table 2. Muscle size and muscle architecture adaptations after training

Study	Sample	Training	Studied muscles	Muscle Size	PA and FL
Aagaard et al. (2001)	11; never participated in a systematic resistance training	14 weeks (38 sessions) heavy resistance training	Vastus Lateralis	Increase in CSAfibre (15.5%), quadriceps ACSA (10.2%), and quadriceps volume (10.3%)	Increase in PA (35.5%)
Alegre et al. (2006)	30 (16 study; 14 control); physically active	13 weeks; 3 days/wk half squat lift	Vastus Lateralis	Increase in MT (7%)	Increase in FL (10.3%). Decrease (2,5% NS) of PA
Baroni et al. (2013)	20 physically active, not enrolled in any lower body resistance training in the past 6 months	12 weeks (1/2 days/wk; total 21 sessions) eccentric training (3-5 sets of 10 reps)	Vastus Lateralis; Rectus femoris	Increase in MT of RF at week 4 (7.4%), 8 (10%) and 12 (9.7%) in comparison to baseline; Increase in MT of VL at week 4 (5.4%), week 8 (6,5%) and week 12 (7%).	NS changes in PA of VL and RF on week 4, 8 or 12; Increases in FL of RF at week 4 (5.9%), 8 (13.8%) and 12 (16.7%); Increases in FL of VL at week 4 (4.5%), 8 (17.3%) and 12 (19.3%).
Cormie et al. (2010)	24 [8 strength training group (ST); 8 power training group (PT); 8 control] with proeficient squat technique	10 weeks (3 days/wk); ST heavy resistance training (75-90% 1RM); PT ballistic jump squat (0-30% 1RM)	Vastus Lateralis	Increase in MT of ST group on both mid-test (5wk: aprox 9%) and post-test (10wk: aprox 12%). No significant changes in MT of PT. Increase in average lean muscle mass of legs in ST (mid-test: aprox 3%; post-test: aprox 4%) but not on PT.	Increase in PA on mid-test (aprox. 7%) and post-test (aprox. 10%) of ST group. NS changes in PA on mid-test of PT group. Increase in PA on post-test of PT group (aprox 7%).
Blazevich & Giorgi (2001)	9 (5 Testosterone, 4 non-Testosterone); well trained	12 weeks; 4 days/wk 2 of them with exercises targeting the triceps	Triceps brachii lateralis	Increase in MT in training group (13.8%) and training + testosterone group (29.5%)	NS changes in PA in training group; Increase PA (39.5%) in training + testosterone group
Blazevich, Gill et al. (2007)	29 (15 study; 14 control); recreationally active	5 weeks; 3 days/wk unilateral isokinetic knee extension training	Vastus lateralis, rectus femoris, vastus medialis, vastus intermedius	No changes in MT in any of the 15 sites tested	NS changes in FL and PA in any of the 15 sites tested
Blazevich, Cannavan et al. (2007)	30 (10 concentric; 11 eccentric; 9 control); recreationally active	10 weeks; 3 days/wk maximal isokinetic concentric or eccentric training	Vastus Lateralis, vastus medialis. PSCA and FL was only measured for vastus lateralis	Increase in whole quadriceps volume (10.2%); VL: Increase in PCSA (7.9%), volume (11.1%), MTprox (10.9%), MTdist (13.6%); VM: Increases in volume (14.8%), MTprox (17.9%), MTdist (12.3%)	VL: Increase in FL Ecc group (3.1%) and Con group (6.3%), PA Ecc group (21.4%), NS changes in PA Con group (13.3%); VM: No changes PA and FL

(Continue)

Table 2. Muscle size and muscle architecture adaptations after training

Study	Sample	Training	Studied muscles	Muscle Size	PA and FL
Blazevich et al. (2003)	23 (8 - squat group [SQ]; 7 forward hack squat group [FHS]; 8 Sprint/jump group [SJ]); well-trained	4 weeks standartization (4 days/wk - 2x RT, 2x S/J); 5 week (SQ and FHS group: 4 days/wk - 2x weight training + 2x S/J; SJ group: 4x S/J)	Vastus lateralis; rectus femoris	SQ group: Changes in MT, VLdist (NS), VLprox (11.1%), RFdist (1.5%), RFprox (7.9%)	Changes in PA: VLdist (NS), VLprox (15.2%), RFdist and RFprox (NS); Changes in FL: VLdist (NS), VLprox (NS), RFdist (22%) e RFprox (83.29%)
				FHS group: Changes in MT: VLdist (NS), VLprox (11.5%), RFdist (27.9%), RFprox (10.9%)	Changes in PA: VLdist (NS), VLprox (13%), RFdist (46.3%), RFprox (NS); Non-significant changes in FL
				SJ group: Changes in MT: VLdist (NS), VLprox (2.9%), RFdist (21.1%), RFprox (20.2%)	Changes in PA: VLdist (-31.3%), VLprox (-6.3%), RFdist e RFprox (NS); Changes in FL: VLdist (80%), VLprox (NS), RFdist (NS) e RFprox (39.17%)
Franchi et al. (2014)	12 (6 concentric, 6 eccentric); not partaking in resistance training	10 weeks; 3days/wk leg press concentric (con) or eccentric (ecc) training	Vastus Lateralis	Signif increase in VL volume (con: 8%; ecc: 6%; no diff. between groups); ACSA proximal (con: -0.5%; ecc: -1%; no dif. between groups); ACSA mid portion (con: 11%; ecc: 7%; between group signif. dif.); ACSA distal (con: 2%; ecc: 8% between group sig dif.)	VL FL: significant increases (con: 5%; ecc: 12%); between group signif. dif. VL PA: significant increases (con: 30%; ecc: 5%); between group signif. dif.
Gondin et al. (2005)	20 (12 study; 8 control); recreationally active but never participated in a systematic strength training	8 weeks; 4 days/wk isometric contractions with electromyostimulation	Knee extensor muscles; vastus lateralis	Significant increases in Quadriceps ACSA (6%)	Significant increase in VL PA (14%).
Kawakami et al. (1995)	5; physically active	16 weeks; 3 days/wk unilateral resistance training of elbow extensors	Triceps brachii (long, lateral and medial head; long head only for PA)	Significant increases in muscle volume (31.7%), ACSAmax (31.7%), PSCA (33.3%), MT (27%).	Significant increase in PA (29.1%); No changes in FL
Matta et al. (2011)	49 (40 study; 9 control); physically active	12 weeks; 2 days/wk strength training	Biceps brachii; triceps brachii (long head)	Significant increases in MT for the 3 studied sites of both biceps and triceps	Signif Increase in PA for 3 studied sites of both biceps and triceps

(Continue)

Table 2. Muscle size and muscle architecture adaptations after training

Study	Sample	Training	Studied muscles	Muscle Size	PA and FL
Narici et al. (2011)	42 (22 study; 20 control); older individuals from less to more experienced in alpine skiing	12 weeks; 2-3 days/wk; 3.5h session; alpine skiing	Vastus Lateralis	Significant increase in MT (7.1%)	Significant increase in FL (5.4%) and PA (3.4%)
Potier et al. (2009)	22 (11 estudo; 11 controle) não treinados	8 weeks; 3 days/wk eccentric training	Biceps femoris	Not assessed	Significant increase in FL (33.5%). No change in PA
Reeves et al. (2004)	18 (9 study; 9 control) older active individuals with no background in resistance traning	14 weeks; 3 days/wk isotonic resistance exercise	Vastus Lateralis	Significant increases in all measure sections of ACSA (3-10% with 6% mean), muscle volume (6%); No increases in muscle PSCA	Significant increase in FL (11%) and PA (13%) during maximal contraction
Ronnestad et al. (2011)	17 (8 study; 9 control) well-trained Nordic Combined	12 weeks; 2 days/wk strength training	Vastus Lateralis	Significant increase in MT (7.4%)	NS changes in either PA and FL
Rutherford & Jones (1992)	12; 4 training for power events, 6 sedentary, 2 unknown	12 weeks; 3 days/wk strength training	Vastus Lateralis (VL), Vastus intermedius (VI)	Significant increase in Quadriceps ACSA (4.6%)	NS change in PA of VI or VL
Seynnes et al. (2007)	13 (7 study; 6 control) recreationally active	5 weeks ; 3 days/wk bilateral knee extension gravity-independent flywheel ergometer	VL, VM, VI, RF, quadriceps. PA and FL was only measured for VL	Significant increase in midthigh CSA: whole quadriceps (7.4%), VL (7.8%), VI (non-significant) ,VM (8.6%), RF (11.4%); Significant increases in distal CSA: whole quadriceps (6.5%), VL (13.8%), VI (6.0%), VM (5.5%), RF (no measure)	Significant increase VL FL (9.9%) and PA (7.7%)

Fiber cross-sectional area (CSAfiber), anatomical cross-sectional area (ACSA), Physiological cross-sectional area (PCSA), cross sectional area (CSA), maximal anatomical cross-sectional aream ($ACSA_{max}$), fascicle length (FL), pennation angle (PA), muscle thickness (MT) distal/proximal (MT_{dist}/MT_{prox}), vastus lateralis (VL) distal/proximal (VL_{dist}/VL_{prox}), rectus femoris (RF) distal/proximal (RF_{dist}/RF_{prox}), vastus medialis (VM), vastus intermedius (VI), non-significant (NS), vastus medialis (VM), significant differences (sig dif.).

3. Methods

3.1. Experimental design

The present study was a *randomized controlled trial* conducted for 15 weeks. The subjects were randomly assigned to one of 2 groups: training group (n = 11) or control group (n = 8). The training group was exposed to 15 weeks of concentric resistance training performed on isokinetic dynamometer (Biodex system 3 research, Shirley, NY, USA). In the training group both legs of all subjects were randomly chose to be trained with either a full (100º of knee flexion to 0º, corresponding to knee fully extended) or partial ROM (60º of knee flexion to 0º). Force (torque max), pennation angle and VL muscle size ($ACSA_{max}$, volume and regional ACSA) were assessed at the beginning and the end of training intervention.

3.2. Subjects

Nineteen male college students were randomly divided into one of two groups, the control group (age, 26.6 ± 5.2 years; height, 177 ± 5.3 cm; body mass, 75.7 ± 10.6 kg; means ± SD) and the training group (age, 21.6 ± 3.5 years; height, 174 ± 4.5 cm, body mass, 71.0 ± 6.9 kg; means ± SD) (Table 3). All subjects were physically active but had no experience in regular and systematic strength training on the 6 months before the beginning of the present study. Exclusion criteria of this study included the presence of any muscular or orthopedic pathology on the lower body.

All subjects were informed of the potential risks of the investigation before signing an informed consent to participate in the study. All procedures were approved by the Ethics Committee of the Faculty of Human Kinetics, University of Lisbon.

Table 3. Means (± SD) of age, height, weight

Group	Age (years)	Height (cm)	Body mass (kg)
Training	21.6 ± 3.5	174.5 ± 4.5	71.0 ± 6.9
Control	26.6 ± 5.2	177.8 ± 5.3	75.7 ± 10.4

3.3. Training program

The training consisted on 15 weeks of concentric knee extension performed on an isokinetic dynamometer (Biodex system 3 research, Shirley, NY, USA). Participants were trained three times per week with a minimum interval of 48 hours between sessions. The attendance of at least 90% of the planned number of sessions, without missing twice in a row, was a requirement for the maintenance of the participants on the present study. With the purpose of a more functional approach, isokinetic angular velocity was increased through the duration of the training program (+30º/s every three weeks). The training program was divided into 5 mesocycles of 3 weeks, increasing the number of sets and/or repetitions in order to maintain TUT (given the increase on isokinetic velocity) during the training intervention. To maintain a high load (low isokinetic velocity) stimulus, 2 sets of 6 (Full group) or 10 repetitions (Partial group) were maintained after the first block to the end of the training intervention. Training design (series x reps @ angular velocity) can be observed in Table 4. Since the angular displacement varies between the member trained with full amplitude (100º of knee flexion to 0º, corresponding to knee fully extended) and the contralateral limb trained with a partial range of motion (60º of knee flexion to 0º), we analyzed the time under tension (TUT) and equalized it for both groups by manipulating the number of sets and/or repetitions (Table 4, Figure 4).

Each training session began with a warm-up consisting of 5 minutes on a cycle ergometer (75-80W), followed by general mobilization of knee joint, and one set of 3 to 5 concentric repetitions of the training exercise at the same velocity used for training. Subjects then trained separately each leg, being one trained with a full ROM (100º of knee flexion to 0º) and the other partial ROM (60º of knee flexion to 0º) as randomly chosed before the beginning of the study.

All subjects completed the training intervention without the occurrence of any injury, and ensuring the pre-determined attendance (42.7 ± 1.1 training sessions with a level of adherence 94.9 ± 2.5%). As such for statistical analysis were included 19 subjects (11 in the training group, 8 in the control group).

Table 4. Comparison of training volume between full and partial ROM groups.

Block	Sets	Reps	Velocity (°/s)	TUT (s)	TUT total (s)
			Full ROM group		
Block 1	5	6	60	50.00	**50.00**
Block 2	5	6	90	33.33	**53.33**
	2	6	60	20.00	
Block 3	5	8	120	33.33	**53.33**
	2	6	60	20.00	
Block 4	6	8	150	32.00	**52.00**
	2	6	60	20.00	
Block 5	6	10	180	33.33	**53.33**
	2	6	60	20.00	
			Partial ROM group		
Block	**Sets**	**Reps**	**Velocity (°/s)**	**TUT (s)**	**TUT total (s)**
Block 1	5	10	60	50.00	**50.00**
Block 2	5	10	90	33.33	**53.33**
	2	10	60	20.00	
Block 3	6	11	120	33.00	**53.00**
	2	10	60	20.00	
Block 4	7	12	150	33.60	**53.60**
	2	10	60	20.00	
Block 5	7	15	180	35.00	**55.00**
	2	10	60	20.00	

Time under tension (TUT)

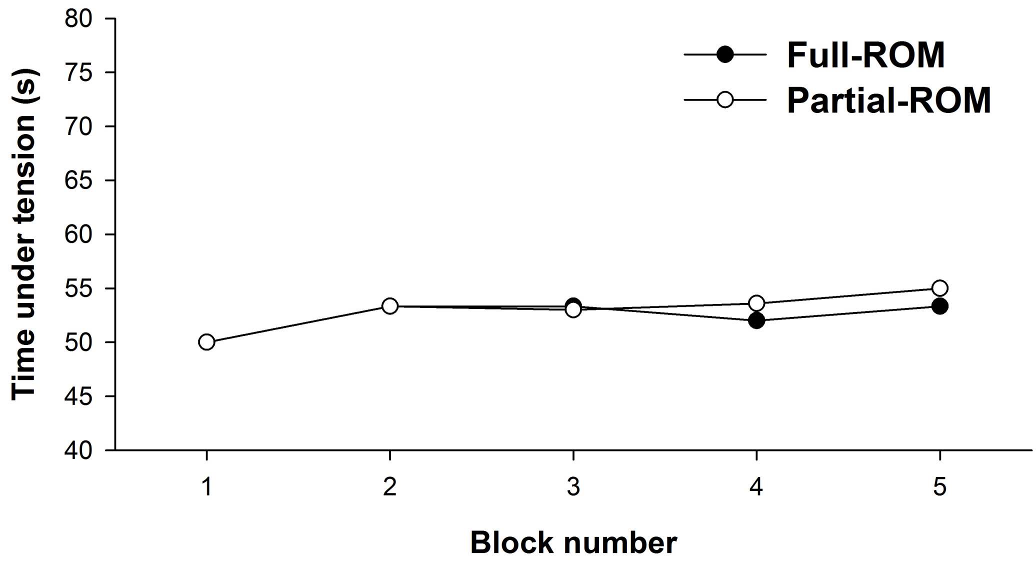

Figure 4. Comparison of training volume between full and partial ROM groups along 5 training blocks. Each block consists on 3 weeks.

3.4. Muscle size assessment

Axial plane scans of the thigh were taken before (1 week) and post-training (4–8 days) in both legs on the training group and randomly on the control group using a 1.5T whole-body MRI scanner (Signa HDxT 1.5T, GE Healthcare, USA). A Proton Density Echo protocol was used (repetition time 4140 ms, echo time, 7.5 ms, Field of View 512 x 512 mm, slice thickness 4 mm, gap between slices, 0.0 mm). Participants were asked to lie supine on the MRI bed and to insert their leg into a pelvic coil. Due to the scanning area of the coil, the thigh was imaged in 2 separate sections. Axial plane scans along the entire length of the VL were collected. From these scans, the contours of the VL muscle on five slices at 25, 50, 75% of total muscle length were digitized using the Osirix image analysis software, and the mean of VL anatomical cross-sectional area (ACSA) and volume for each region was calculated (Figure 5). From the sum of the volume of the three regions, VL total volume was also calculated. Moreover, the maximal anatomical cross-sectional area ($ACSA_{max}$) was identified from all measured slices. Total Muscle length was defined as the distance between the axial slices where the VL muscle was visible starting from the hip/knee joint (proximal and distal portions, respectively).

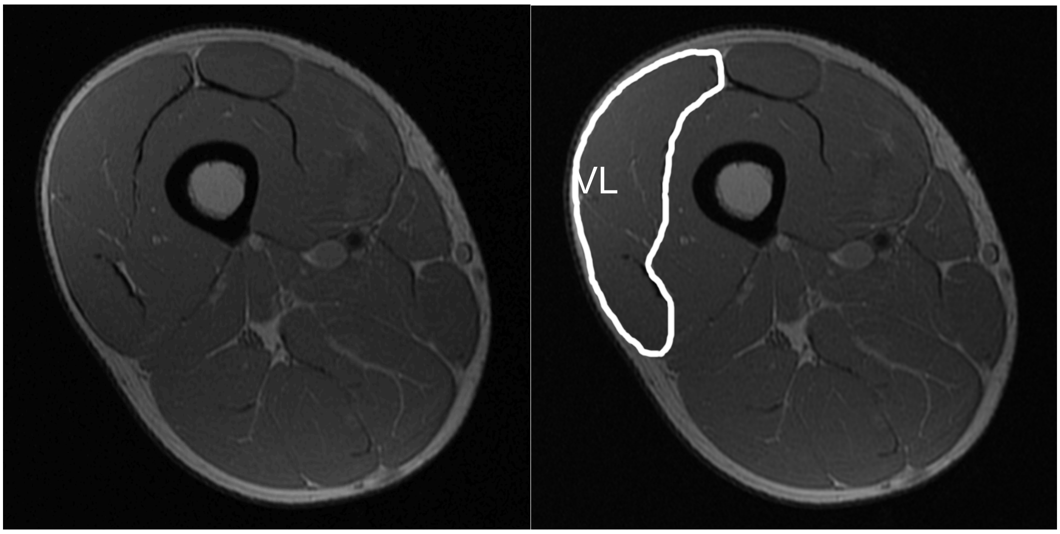

Figure 5. MRI scan of the quadriceps muscles. Perimeter of the vastus lateralis (VL) is delimited on the right image.

3.5. Pennation angle assessment

Two-dimension B-mode ultrasonography (EUB-7500, Hitachi Medical Corporation, Tokyo, Japan) with a 9-cm, 10-MHz linear-array probe was used to measure *in vivo* pennation angle of vastus lateralis. Sonographs were taken before (1 week) and post-training (4–8 days) in both legs on the training group and randomly on the control group. During ultrasonography measures participants were seated in an upright position on the isokinetic dynamometer device with the leg at 10º of knee flexion. Before scans were taken information was given to all participants to remain relaxed. To ensure that the probe was effective placed in both testing occasions, scanning sites of all subjects both legs were mapped with a malleable transparent plastic sheet at the baseline (Blazevich, Cannavan, et al., 2007; Blazevich, Gill, et al., 2007). Scans were taken with the probe perpendicular to the dermal surface and oriented along the sagittal plane of the fascicles at 50% between the greater trochanter and the lateral condyle as commonly used in muscle architecture research (Alegre et al., 2006; Baroni et al., 2013; Blazevich, Cannavan, et al., 2007; Cormie et al., 2010). To avoid contact with the skin, the probe was coated with a water-soluble transmission gel. This procedure avoids acoustic noise. Sonographs were saved when they were clearly visible. Five measures of PA were obtained in each of the three images taken from each subject leg. Therefore, fifteen values of PA were obtained for each subject and assessment time. The mean of the 15 measured values was used for analysis. A total of 180 images of control (pre: 24; and post intervention: 24) and training group (pre:

66; and post training intervention 66) were saved for later examination (Figure 1,2). Images were examined using the digitizing software *ImageJ 1.46r* (National Institutes of Health, Bethesda, MD, USA).

3.6. Knee extension isometric torque assessment

After warm-up, concentric isometric knee extension torque output was measured separately for each leg and used as strength score. For the control group the leg was chosen randomly. Torque was measured with the subjects seated in an upright position on the isokinetic dynamometer device with the leg at 75º of knee flexion. Information was given to all participants to hold 3 (rest interval of 2 minutes) maximal isometric contractions of the knee extensor muscles for 5 seconds. The torque signal was A/D converted (MP100 – Biopac™ Systems, 16bits) with a sample rate of 1000Hz and filtered with a low-pass filter with a cutoff frequency of 16 Hz. The peak torque was calculated as the higher value of the force-time curve, and was used for analysis.

3.7. Statistical analysis

The data collected were analyzed using the statistic program SPSS Statistics for Macintosh version 19.0.0, 2010 (SPSS Inc., IBM Company, Chicago). The *Shapiro-Wilk* test was performed to check the condition of normality of the sample for each variable. The mean and respective standard deviations were calculated in the initial descriptive statistical analysis. The changes (Δ) between pre and post-measurements for $ACSA_{max}$, VOL_{total}, $ACSA_{25}$, $ACSA_{50}$, $ACSA_{75}$, VOL_{25}, VOL_{50}, VOL_{75}, PA and FL were obtained. To check the differences between groups (control, partial ROM and full ROM) an *one-way ANOVA*, together with a *Scheffe post-hoc test* was used to compare each change (Δ). Whenever homogeneity of the variances was not observed, a *Welch comparison test* was performed together with *Tamhane T2 post-hoc test.* To check the differences on each group between muscle size measured sites (i.e. $ACSA_{25}$ vs. $ACSA_{50}$ vs. $ACSA_{75}$) an one way repeated measures ANOVA was performed. A significance level of $p < 0.05$ was considered in all statistical tests. Results are presented in the tables and text as means +/- SD and in figures as means +/- SEM.

4. Results

4.1. Muscle size

VL volume and maximum ACSA

Vastus lateralis volume and $ACSA_{max}$, increased from pre- to post-training on both training groups. On the concentric partial range of motion group (PAR), vastus lateralis volume and $ACSA_{max}$ increase from 164.22 ± 17.63 to 171.75 ± 18.61 cm^3 ($p < 0.05$) and 33.69 ± 3.77 to 35.06 ± 3.94 cm^2 ($p < 0.05$), corresponding to a relative change of 4.6 ± 1.11 % and 4.07 ± 1.31 %, respectively. On the concentric full range of motion group (FULL), vastus lateralis volume and $ACSA_{max}$ increase from 165.74 ± 18.75 to 174.18 ± 19.06 cm^3 ($p < 0.05$) and 33.71 ± 4.18 to 35.49 ± 4.30 cm^2 ($p < 0.05$), corresponding to a relative change of 5.1 ± 1.25 % and 5.25 ± 1.51 %, respectively (Figure 6). When comparing between training groups, no significant ($p < 0.05$) differences were observed in VL volume or $ACSA_{max}$ (Figure 6). Also, no significant differences were observed in control group for VL Volume and $ACSA_{max}$ (Figure 6).

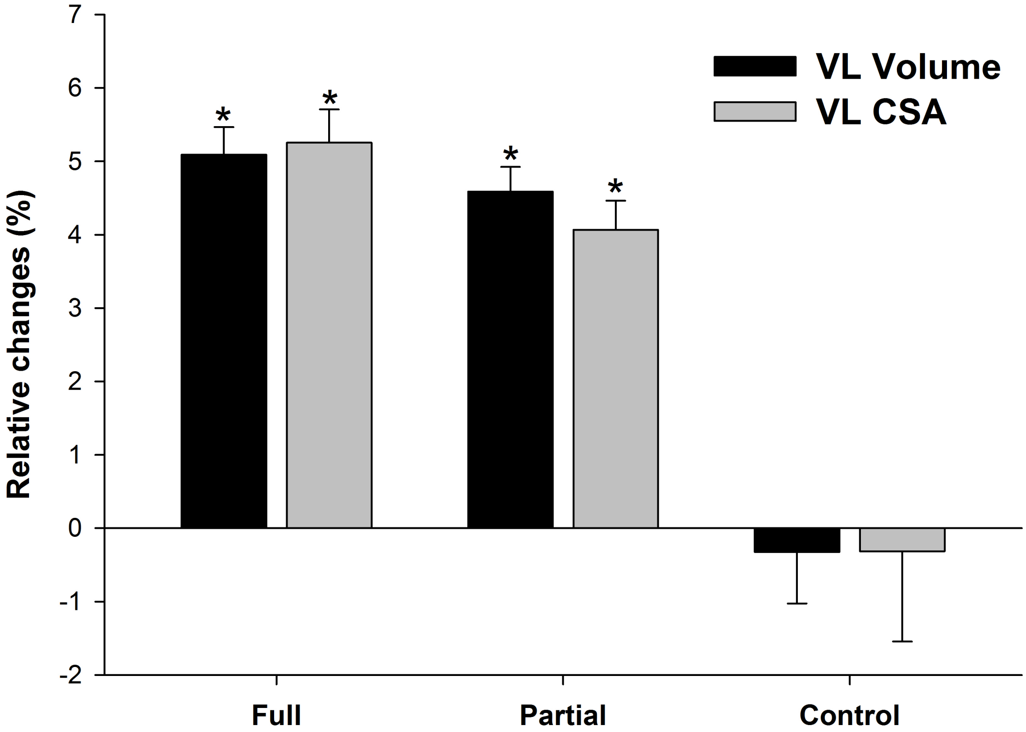

Figure 6. Relative changes in VL Volume and maximum ACSA ($ACSA_{max}$), after training with full ROM (Full), training with partial ROM (Partial) and control (Control). Columns show group adaptation mean (%), and standard error of the mean (SEM) is indicated by errors bars. No differences on changes of control group. No differences between training groups. *Significant different from control group ($\rho < 0.05$).

VL regional muscle size adaptations

Anatomical VL ACSA increased after 15 weeks in all measured regions on both training groups with no significant differences between groups ($p < 0.05$) (Table 5, Figure 7). As expected, no changes on control group were found (Table 5, Figure 7). We found no differences between distal and middle VL muscle size, although both regions were significant different from proximal region in both training groups (Table 5, Figure 7). Although no significant differences were observed between distal and middle measured sites, there was a trend for a greater increase in VL ACSA and volume from proximal to distal (Table 5, Figure 7).

Table 5. Changes in anatomical cross-sectional area of the Vastus lateralis (VL) measured on three muscle regions: proximal (25% of the length of the muscle), medial (50% length) and distal (75% in length). The mean and standard deviation of the respective anatomical sections 5 values are displayed. No differences were found on the control group. No differences were found between medial and distal regions on both training groups, or between any regions on control group. *Significant different from control group ($\rho < 0.05$). #Significant different from proximal region ($\rho < 0.05$).

	Proximal			
Group	Pre-training (cm^2)	Post-training (cm^2)	Changes (cm^2)	Changes (%)
Full	26.5 ± 2.5	27.3 ± 2.6	0.8 ± 0.4	**3.0***
Partial	26.4 ± 2.8	27.2 ± 2.9	0.8 ± 0.3	**2.9***
Control	25.4 ± 4.2	25.3 ± 4.3	-0.1 ± 0.5	**-0.4**

	Medial			
Group	Pre-training (cm^2)	Post-training (cm^2)	Changes (cm^2)	Changes (%)
Full	33.3 ± 4.1	35.1 ± 4.2	1.8 ± 0.5	**5.5*#**
Partial	33.1 ± 3.7	34.6 ± 3.9	1.5 ± 0.5	**4.5*#**
Control	32.6 ± 4.7	32.4 ± 5.4	-0.2 ± 1.1	**-0.5**

	Distal			
Group	Pre-training (cm^2)	Post-training (cm^2)	Changes (cm^2)	Changes (%)
Full	23.1 ± 3.3	24.7 ± 3.4	1.6 ± 0.5	**6.9*#**
Partial	22.6 ± 3.2	24.1 ± 3.5	1.5 ± 0.5	**6.7*#**
Control	22.4 ± 3.7	22.4 ± 4.2	0.0 ± 0.8	**0.0**

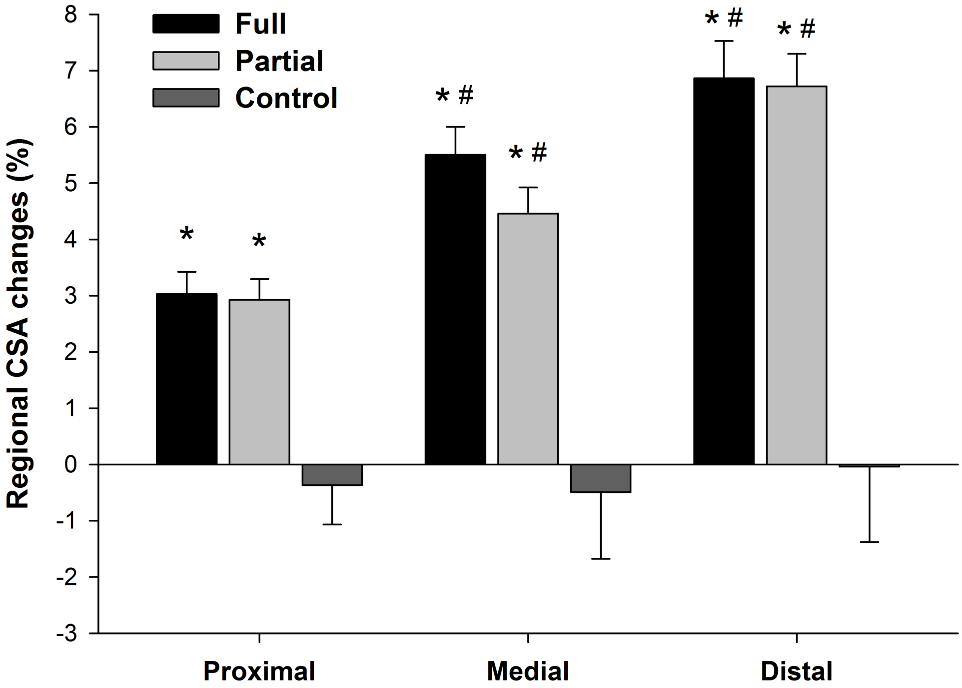

Figure 7. Relative changes on regional VL ACSA, after training with full ROM (Full), training with partial ROM (Partial) and control (Control). Columns show group adaptation mean (%), and standard error of the mean (SEM) is indicated by errors bars. No differences were found between medial and distal regions on both training groups, or between any regions on control group. *Significant different from control group ($\rho < 0.05$). #Significant different from proximal region ($\rho < 0.05$).

4.2. Pennation angle

VL pennation angle increased from pre- to post-training in both training groups, whereas no significant changes ($p < 0.05$) were observed in the control group or when comparing between training groups (Figure 8). Pennation angle increased from 15.51 ± 1.67 to 17.41 ± 1.82 deg ($p < 0.05$) in PAR and 15.50 ± 1.57 to 16.97 ± 1.62 deg ($p < 0.05$) in FULL, corresponding to a relative change of 12.32 ± 2.44 and 9.58 ± 2.37 %, respectively.

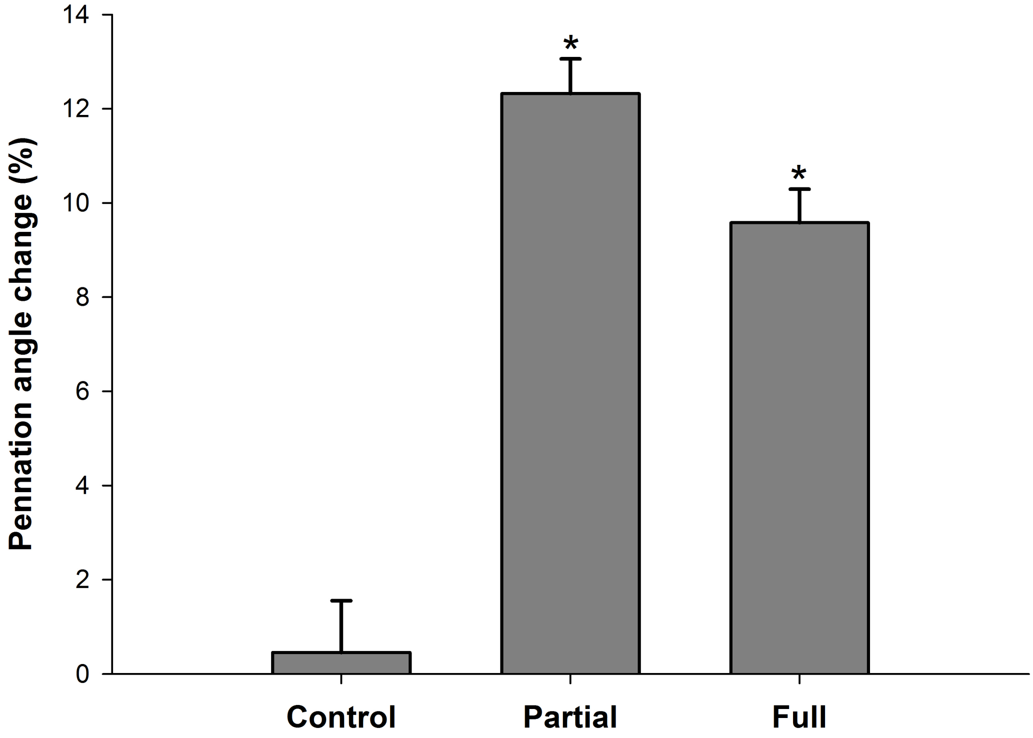

Figure 8. Relative changes in VL PA measured at 50%, after training with full ROM (Full), training with partial ROM (Partial) and control (Control). Columns show group adaptation mean (%), and standard error of the mean (SEM) is indicated by errors bars. No differences between training groups. No differences from pre- to post-training in the control group. *Significant different from control group (ρ < 0.05).

4.3. Knee extension maximal torque

Knee extension maximum torque increased from pre- to post-training in both training groups, with no significant differences between groups ($p < 0.05$). In contrast no changes were observed in control group (Figure 9). Force increased from 292.25 ± 54.59 to 365.38 ± 44.86 Nm ($p < 0.05$) in PAR and 290.67 ± 44.97 to 383.82 ± 56.13 deg ($p < 0.05$) in FULL, corresponding to a relative change of 27.89 ± 20.35% and 33.19 ± 16.78, respectively.

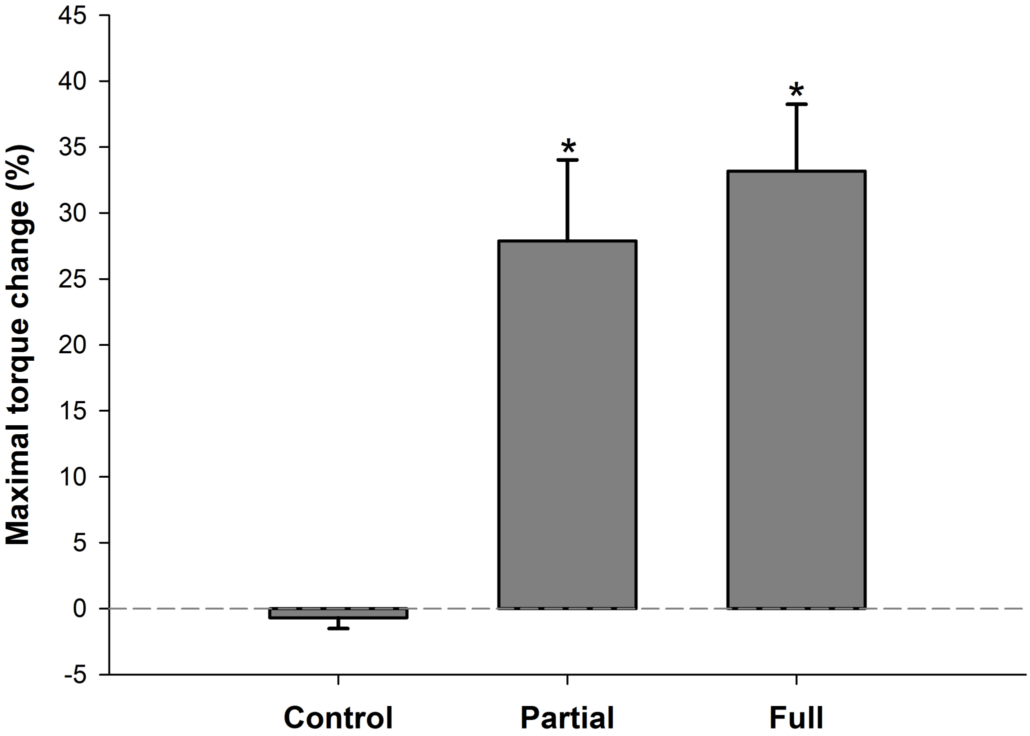

Figure 9. Relative changes in force, measured as maximum knee extension torque, after training with full ROM (Full), training with partial ROM (Partial) and control (Control). Columns show group adaptation mean (%), and standard error of the mean (SEM) is indicated by errors bars. No differences between training groups. No differences from pre- to post-training in the control group. *Significant different from control group ($\rho < 0.05$).

5. Discussion

We analyze the effects of 15 weeks of unilateral knee extension isokinetic resistance training with either a full or partial ROM, on VL muscle size, muscle architecture and maximal isometric knee extension torque. Briefly, muscle size was assessed on three different regions of the studied muscle (25, 50 and 75%) using MRI. Pennation angle was measured at a single region (50%) before and after the training intervention. Maximal isometric torque was measured on isokinetic device with knee flexed at 75º. A novelty of the present study was the equalization of muscle time under tension between both intervention groups (full and partial). Moreover, in our best knowledge this was the first study that analyzes the influence of ROM resistance training on muscle structure in isokinetic conditions.

Muscle size

As we hypothesized, an increase in VL muscle size was observed on both training groups. Increases in muscle fiber size (hypertrophy) (Aagaard et al., 2001; Akima et al., 1999; Andersen & Aagaard, 2000; Hikida et al., 2000; Sharman et al., 2001; Staron et al., 1994; Volek et al., 1999) and changes on the arrangement of muscle fibers (or fascicles) (Blazevich & Giorgi, 2001; Blazevich et al., 2003; Seynnes et al., 2007) were previously observed as an adaptation to resistance training. The combinations of both, together with other factors (e.g. extracellular matrix), are responsible for muscle size increases. In our study we did not analyze muscle fiber CSA directly, nevertheless the increases on VL volume (Full=5.1%; Partial=4.6%), CSA_{max} (Full=5.3%; Partial=4.1%) and volume/ACSA measured at middle region (Full=5.5%; Partial=4.5%) suggest hypertrophy of VL muscle fiber CSA (Aagaard et al., 2001). Although significant, our results are lower in comparison to previously data on VL adaptation after resistance training. The difference becomes even more pronounced when we consider that our intervention was longer than the majority of previously research. Blazevich, Cannavan, et al. (2007) reported an increase of 11.1% on VL volume after only 10 weeks of isokinetic concentric or eccentric knee extension training (no between-groups difference). Similar results of 10.2% were observed by Aagaard et al. (2001) on ACSA of VL measured at midway of total femur length, after 14 weeks of strength training. Also Franchi et al. (2014) reported an increase of ~7% on VL volume after 10 weeks of leg press exercise training. Even more pronounced increases were reported by Seynnes et al. (2007). The authors reported an increase of 9.0 ± 3.7% ($p < 0.05$) after 20 days, and 13.8 ± 3.1% ($p < 0.01$) after 35 days of training on a gravity-independent flywheel equipment. The lower results on muscle size adaptations observed in our study can be partially explained by the force-velocity relationship in concentric muscle actions (Fenn & Marsh, 1935; Wilkie, 1949). The progressive increase (30 º/s every 3 weeks of training) of the isokinetic training velocity, could have caused a drop on the necessary mechanical stimulus for muscle hypertrophy optimization. Results from the study of Cormie et al. (2010) support the lower magnitude of gains we observed in our study. The authors found no significant changes on VL MT after 10 weeks of ballistic jump squat with 0-30%RM. However in the same study, a significant increase of ~12% was observed in the group training with higher loads (75-90%RM). The results from the study of Blazevich, Gill, et al. (2007) whom trained the subjects for 5 weeks (3x/week) with a higher isokinetic velocity in comparison to the used in the study of Blazevich, Cannavan, et al. (2007) (60º/s vs. 30º/s, respectively) also support our findings. While in the study of Blazevich, Gill, et al. (2007) there were no significant changes on VL MT, Blazevich, Cannavan, et al. (2007) reported a significant increase VL MT after 5 weeks of isokinetic knee extension training. Hypertrophy of muscle fiber result from an increase in sarcomeres arranged in parallel, in series or a combination of both as observed directly in animal studies (Butterfield et al., 2005; Lynn et al., 1998; Paul & Rosenthal, 2002) or in Human muscle architecture (fascicles arrangement) research (Aagaard et al., 2001; Baroni et al., 2013; Blazevich, Cannavan, et al., 2007; Reeves et al., 2004). Together with other training variables, an increase in time under tension and force produced are responsible for a greater hypertrophic response (Schoenfeld, 2010, 2013). Given the force/velocity relationship (Fenn & Marsh, 1935; Wilkie, 1949), a greater isokinetic velocity is associated with lower force and time under tension. In our study, we trained our subjects with isokinetic velocities up to 180º/s. Even increasing the volume (sets x reps) in order to mantain TUT from training block to training block (Table 4) the low force imposed by the high velocity might have limited gains in muscle size in comparison with other studies.

Because non-linear changes in muscle size within VL were previously observed (Blazevich et al., 2003; Häkkinen et al., 2001; Housh et al., 1992; McMahon et al., 2013; Narici, Hoppeler, et al., 1996; Reeves et al., 2004), we also calculate volume and mean cross-sectional area for 25, 50 and 75% of total VL muscle length. Significant increases on regional VL ACSA in comparison to baseline were found in all measured sites, with no differences between training groups (Table 5, Figure 7). As expected, no differences were found in control group (Table 5, Figure 7). Commonly, greater hypertrophy occurs in the region of largest CSA of QF (normally at midthigh), decreasing toward the proximal and distal sites (Häkkinen et al., 2001; Housh et al., 1992; McMahon et al., 2013; Narici, Hoppeler, et al., 1996; Tracy et al., 1999). Although, and even QF group increases more at midthigh this may not correspond to individual portions adaptation (Narici, Hoppeler, et al., 1996; Tracy et al., 1999). In our study we found no differences between distal and middle VL muscle size, although both regions were significant different from proximal region (Table 5, Figure 7). Although no significant differences were observed between distal and middle measured sites, there was a trend for a greater increase in VL ACSA and volume from proximal to distal (Table 5, Figure 7). Similar results were found by Housh et al. (1992) whom verified increases of 1.1, 8.0 and 13.4% on VL ACSA measured at a proximal, medial and distal level after 8 weeks of isokinetic concentric leg extension/flexion training. Nevertheless, only the medial level (8.0%) was significant greater in comparison to baseline. The mechanisms underlying this preferential hypertrophy are complex and not fully understood. One possible explanation might be the longitudinal amount of force transmitted along muscle length as demonstrated by the differences from proximal to distal regions in rats (Huijing & Baan, 2001; Yucesoy, Maas, Koopman, Grootenboer, & Huijing, 2006). Given the importance of the mechanical tension on muscle hypertrophy, the differences observed in force along muscle length can explain the heterogeneous regional hypertrophy (Schoenfeld, 2010). A detailed review on this subject can be read in the review of Huijing & Jaspers (2005).

When comparing between training groups, we found no significant differences in any of the muscle size measurements. As previously discussed increases in muscle size reflects an increase in FL (Baroni et al., 2013; Reeves et al., 2004), PA (Aagaard et al., 2001) or a combination of both (Blazevich, Cannavan, et al., 2007). Therefore, when combining results from muscle size (greater on FULL vs. PAR, not reaching statistic significance) with pennation angle (lower on FULL vs. PAR, not reaching statistic significance) suggest a greater increase in FL of the FULL group. In other words, we speculate that muscle size increase slightly more in FULL as result of FL increases. As observed in humans (McMahon et al., 2013) and animals (Burkholder, 2001; Koh & Herzog, 1998), FL are sensible to training ROM. In the present study the FULL group trained with amplitudes (100º) higher then everyday routines (Blazevich, Cannavan, et al., 2007), therefore resulting on greater muscle excursions and possible greater FL and consequently muscle size (Baroni et al., 2013; Reeves et al., 2004). Also, training at a higher knee angle will result in a greater internal force (Kubo et al., 2006). In instance, Kubo et al. (2006) determined that internal VL was 2.3 times greater on an isometric knee extension at 100º (knee flexion) in comparison to 50º (knee flexion). In our best knowledge, only two other studies analyzed the influence of ROM training on lower body muscles adaptation (Bloomquist et al., 2013; McMahon et al., 2013). Bloomquist et al. (2013) observed significant differences on all front thigh muscles CSA slices but not on MT of VL (measured 50% between the greater trochanter and the lateral condyle) concluding that increases on front thigh muscles CSA can be better explained by the increase of other muscles rather than VL. McMahon et al. (2013) compaired the effect of ROM (large ROM group: 0-50º and shorter ROM group: 0-90º of knee flexion) after 8 weeks of lower body inoinertial resistance training. The authors verified a significant greater increase on the group who trained with a larger ROM in comparsion to the group who trained with a shorter ROM on VL ACSA measured at 75% of total femur length. However no differences were found between groups on the other two regions (25, 50%), concluding that the observed discrepancies in CSA between groups may be explained by the regional differences in the total stimulus (i.e. force generation and stretch) transmitted along the length of the muscle. Nevertheless, it is important to mention that in both studies timer under tension was not equalized. Probably, if in the studies of Bloomquist et al. (2013) and McMahon et al. (2013), TUT was increased in the smaller ROM group in order to be equal to the larger ROM group, the differences between training groups would be minor or statistically inexistent. In our study training volume (sets x reps) was increased in lower ROM group in order to be similar to the larger ROM (using TUT as reference). Being that, we found no significant differences between training groups on any measure of muscle size (Table 5, Figure 6, Figure 7).

Pennation angle

We hypothesized an increase on PA after the training intervention. Previously research verified increases on PA after systematic resistance training performed on isokinetic conditions (Blazevich, Cannavan, et al., 2007) or other more conventional training equipment as free weights (Blazevich et al., 2003; Bloomquist et al., 2013; Cormie et al., 2010), resistance training machines (Franchi et al., 2014; Reeves et al., 2004; Seynnes et al., 2007), or combination of both (Aagaard et al., 2001; McMahon et al., 2013). An increase in PA allow for a greater amount of contractile material to be attached in a given area (Jones & Rutherford, 1987; Kawakami et al., 1995; Lieber & Fridén, 2001), therefore contributing for an increase in muscle size (Aagaard et al., 2001; Fukunaga, Kawakami, et al., 1997; Rutherford & Jones, 1992) and force (Aagaard et al., 2001; Fukunaga et al., 2001; Narici, 1999). Given that we expected PA to follow the observed increases on muscle size, specially those observed at the same region (50% of total femur length). According to our expectations, PA significantly increase 12.3 ± 2.44% in PAR and 9.6 ± 2.37% in FULL, whereas in contrast no significant changes were observed in the control group (Figure 8).

Different magnitudes of VL PA adaptation can be observed in the literature as demonstrated by the 35.5% observed in the study of Aagaard et al. (2001) in comparison to the significant decrease observed in the studie of Blazevich et al. (2003). Training variables (i.e. intervention duration, load dynamic, equipment), sample characteristics (i.e. training background), and muscle region assessed, influence muscle architecture adaptation (Table 2 for a more detailed analysis of training studies). Differences on the training and study variables complicate results comparison between studies. Nevertheless similar increases (13%) on PA of VL as response to 14 weeks (3x/week) of bilateral knee extension and leg press exercises were observed in elderly (Reeves et al., 2004). Also, Blazevich, Cannavan, et al. (2007) reported a similar increase of 13.3% on PA of VL after 10 weeks (3x/week) of concentric isokinetic at 30º/s. However, it was insufficient to reach statistical significance. Nevertheless, greater increases on VL PA have been reported in the literature as the 35.5% observed by Aagaard et al. (2001) after 14 weeks of isotonic resistance training, ~23% observed by Bloomquist et al. (2013) after 12 weeks of squat training or the 30% observed by Franchi et al. (2014) after 10 weeks of concentric leg press training. The program design we have used in the present study consisted in isokinetic velocity increments every 3 weeks (Table 4). Low-load / high-velocity training is associated to a decrease or lack of changes on PA (Alegre et al., 2006; Blazevich et al., 2003; Cormie et al., 2010). When comparing strength (low velocity / high load) with power (high velocity / low load) training, Cormie et al. (2010) verified a significant increase in VL PA on the strength group but not on power group after 5 weeks of training. Also Alegre et al. (2006) observed no changes on PA of VL after 13 weeks of half squat lift with low load (30-60%RM) high velocity. Blazevich et al. (2003), found significant decreases on VL PA (proximal and distal) after 5 weeks of sprint and jump training. As demonstrated schematically by Kumagai & Abe (2000), a smaller pennation angle associated with a greater fascicle length and muscle thickness will result in an increased muscle shortening velocity. Therefore differences in PA adaptation can be expected given the force/velocity characteristics of the training design (Blazevich et al., 2003). Being that, larger increases in PA could possible been limited by the high velocity we have used in the last training blocks (120, 150, 180º/s). It is possible that the observed adaptations on PA was a consequence of the first blocks, where the velocity was lower (60 and 90º/s) and remains until the post-training assessments since a low velocity stimulus (2x60 at 60º/s and 2x10 at 60º/s on full and partial ROM, respectively) was maintained during the duration of the training intervention. A more traditional periodization program with increase on intensity (i.e. decrease on isokinetic velocity) and volume could therefore lead to greater PA increases as in the studies of Aagaard et al. (2001), Bloomquist et al. (2013) or Franchi et al. (2014).

When comparing differences between training groups, no significant differences were found between the group who trained with full ROM and the group who trained with partial ROM (Figure 8). In agreement with our findings, similar results were observed in the only two studies we found in literature that analyze effects of ROM training on muscle architecture adaptation (Bloomquist et al., 2013; McMahon et al., 2013). Nevertheless, McMahon et al. (2013) refer a tendency for a greater increase in PA (across the 3 measured sites of VL) on the larger ROM group (11 ± 5%) in comparison to the shorter ROM group (7 ± 4%). As suggested by the authors, differences on ROM training represent different physical demands, resulting in a greater stress in the larger ROM group knee extensors. Therefore if training volume were equalized between training groups, this observed trend would not probably exist. To address this, in our study training volume was equalized between training groups (Table 4, Figure 4). VL PA of PAR group increased more then the VL PA of FULL group, although no significant differences between groups were observed. Similar results were obtained in the study of Bloomquist et al. (2013) where the group that trained with lower amplitude had very slight increases compared to the group that trained with greater amplitude. Possibly, if the volume was equalized as in our study, a greater increase on PA of the lower ROM group in comparison to the higher ROM group would be observed. Because fibers of the pennate muscles rotate during contraction (Fukunaga et al., 1997; Gans & Gaunt, 1991; Kawakami et al., 1998), it is possible that when working with a shorter ROM the fascicles are mechanically stressed at greater PA. This can in part justify the slightly non-significant increases on PA we observed between PAR and FULL groups, respectively 12.32 ± 2.44 and 9.58 ± 2.37 %. As was recently conducted in the study of Franchi et al. (2014) a transversal study analyzing the architectural acute behavior to different ROM would be beneficial to better understanding the results.

Knee extension maximal isometric torque

Maximal torque increased independently of ROM in the present study (Figure 9). These findings are supported by some authors (Graves et al., 1992; Massey & Vincent, 2004) but not others (Bloomquist et al., 2013; Clark et al., 2011; Graves et al., 1989; Kubo et al., 2006; Massey & Vincent, 2005; McMahon et al., 2013; Pinto et al., 2012; Weiss et al., 2000). In what concerns to lower body, angle specific adaptations to ROM training are observed (Bloomquist et al., 2013; Kubo et al., 2006; McMahon et al., 2013; Weiss et al., 2000). Greater increases on strength were observed thru wider amplitudes on subjects who trained with higher ROM, both isometrically (Kubo et al., 2006) and dynamically (Bloomquist et al., 2013; McMahon et al., 2013; Weiss et al., 2000). Nevertheless, in previously ROM training studies time under tension was not controlled. Therefore, when subjects train with larger ROM and equal training volume (sets x reps) they are exposed to a greater TUT and training stimulus. For instances, when comparing ROM bench press in 4 conditions (full bench press ROM, ¾ ROM, ½ ROM, ¼ ROM), Clark et al. (2008) observed an increase on each repetition mechanical work. Time under tension is known to be an important variable when seeking muscle hypertrophy (Burd et al., 2012; Schoenfeld, 2010, 2013). Because force is proportional to CSA (Aagaard et al., 2001; Fukunaga et al., 1996; Fukunaga et al., 2001; Maughan, Watson, & Weir, 1984), it is expected that groups exposed to a greater ROM, and consequently a greater TUT, increase more muscle force (Bloomquist et al., 2013; McMahon et al., 2013; Weiss et al., 2000). Given that, we strongly believe that the greater increases observed in literature on the groups exposed to greater ROM results from the observed increases on muscle size (Bloomquist et al., 2013; McMahon et al., 2013). In our study we used TUT in order to equalize training volume (sets x reps) between training groups. As can be observed in table 4, the number of sets and/or reps was increased on PAR group. Nevertheless, the slightly greater increases on knee extension maximal torque in the FULL group can result from the small (non-significant) increases on muscle size, which as previously discussed can be consequence of the increased muscle mechanical stress or increased muscle excursion. Another possible explanation for the small differences observed in our study is the angle chosen to assess knee extension torque (75º). Because PAR group trained from 60-0º of knee flexion, the lower results on maximal torque observed in comparison to the FULL group (not statistically) might be consequence of assessing the torque on different amplitude than that used for training. This specificity of adaptation has been previously demonstrated after isotonic (Bloomquist et al., 2013; McMahon et al., 2013; Weiss et al., 2000) and isometric (Kubo et al., 2006) resistance training.

6. Conclusion

We observed a significance increase on vastus lateralis muscle size, fascicle angle and maximal isometric knee extension torque after 15 weeks of a full or partial isokinetic concentric training protocol. Nevertheless, no differences were found when comparing adaptation between training groups. Because previously research did not equalize training volume, it is hard to understand if their findings arise from differences on the training volume or from the manipulation of training range of motion. In our best knowledge the present study was the first to equalize training volume based on time under tension. Given that, when muscle time under tension is equalized, the manipulation of training ROM seems to have minor to no effect on adaptation of VL muscle size, pennation angle or muscle force assessed as maximal isometric knee torque at 75º. However, it is important to note that the periodization scheme used in our study consisted on increasing dynamometer velocity every 3 weeks. Moreover, a concentric only type of contraction was used for training the subjects. Given the force x velocity curve, when increasing the concentric isokinetic velocity, the force produced is diminished. This will ultimately result on a lower mechanical stress for hypertrophy adaptations, and possible limit the absence of differences observed on muscle size and pennation angle between training groups. Consequently, this speculation can be extended for the non-significant differences we found on maximal isometric knee extension torque measured at 75º between the FULL and PAR group.

Given the training characteristics and the duration of intervention we have observed minor, non-significant differences when comparing training with a FULL versus PAR ROM on VL muscle size, pennation angle and maximal isometric knee extension torque measured at 75º of knee flexion. The similar adaptations on muscle size and pennation angle between different ROM training could be advantageous in knee rehabilitation protocols where ROM should be controlled and muscle training/strength is the aim of the protocol. Moreover, our findings on maximal isometric knee extension torque suggest that apparently there is no major advantage to reduce training ROM when seeking force-related adaptations. Nevertheless, maximal torque was only measured isometrically at a single angle (75º). To better understand how knee extensor muscles adapts to ROM training (i.e. force-velocity and force-length relationships), a more complete assessment with other angles and different isokinetic velocities is recommended. As described on the introductory chapter of this thesis, the present investigation was part of a larger project on strength training and muscle architecture. This project has investigated many other variables and experimental conditions, which will contribute for a better understanding of the research questions which where addressed on the present study.

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